AD-618135

RESTRICTED

WATERTOWN ARSENAL

LABORATORY

REPORT

NO. WAL 731/281

PROGRESSIVE STRESS DAMAGE AND STRENGTH OF CENTRIFUGALLY CAST, COLDWORKED GUN TUBES

BY
Donald H. Newhall
Capt., Ord Dept. Res.

Peter R. Kosting
Metallurgist

DATE 17 June 1949

WATERTOWN ARSENAL
WATERTOWN, MASS.

RESTRICTED

ERRATA SHEET

WAL Report No. 731/281(R)
O.O. Project TR3-5003C

TITLE: PROGRESSIVE STRESS DAMAGE AND STRENGTH OF CENTRIFUGALLY CAST, COLDWORKED GUN TUBES.

(1) Page 5, paragraph 5, line 6 - change to:

$$a = \frac{1}{2} \cdot \frac{W-1}{W^2-1} \cdot \frac{id}{ts} \sqrt{(ts)^2 (W^2-1)^2 - (IP)^2 (1.5 + W + W^4)}$$

(2) Appendix C, page 7, paragraph 2, line 10, add:

"after being modified" so as to read - . . . "was found to be accurate after being modified when" . . .

(3) Page 8, paragraph 1, line 4, Equation (1), change to:

$$a = \frac{1}{2} \cdot \frac{W-1}{W^2-1} \cdot \frac{id}{ts} \sqrt{(ts)^2 (W^2-1)^2 - (IP)^2 (1.5 + W + W^4)}$$

(4) Page 8, paragraph 1, line 5, add:

"and modified" so as to read - . . . "developed by Flair[14] and modified is used, namely," . . .

(5) Page 8, paragraph 1, line 6, change to:

$$bpf = \frac{W^2-1}{\sqrt{1.5 + W + W^4}}$$

(6) Figure 28: At the large values of wall ratios, curves range from zero to 1/2% low and at small value of wall ratios, curve ranges from zero to 5% low.

RESTRICTED

UNCLASSIFIED

WAL 731/281

O. O. Project Number TB3-3003C

PROGRESSIVE STRESS DAMAGE AND STRENGTH

OF CENTRIFUGALLY CAST, COLDWORKED GUN TUBES

UNCLASSIFIED

RESTRICTED

WATERTOWN ARSENAL LABORATORY

Authorized by:	ORDTR-Cannon	17 June 1949
O.O. Project Number:	TR3-3003C	
Report Number:	48th Partial, WAL 731/281	
Priority:	2C	
Title of O.O. Project:	Cannon Tubes - Progressive Stress Damage In	
WAL Project No.:	3.31-F	

TITLE

Progressive Stress Damage and Strength of Centrifugally Cast, Coldworked Gun Tubes

OBJECT

1. To determine the resistance to progressive stress damage of centrifugally cast, coldworked, production gun tubes by evaluating the effect of the following factors upon the life of cannon sections when subjected to repeated applications of high hydraulic pressure:

   a. Yield strength before coldwork in the range 85,000 to 150,000 psi
   b. Percent of coldwork ranging from 0 to 6.0
   c. Wall ratio in the range 1.2 to 1.8
   d. Rifling, using smooth bore, "Rib" rifling and "French" rifling
   e. Proof-firing

2. To determine the strength of such cannon sections which had various amounts of metal removed by machining from the outside surface after coldworking and rifling.

3. To arrange the results so that engineers may incorporate progressive stress damage in design of cannon tubes.

4. To determine the elastic modulus of the coldworked metal.

5. To evaluate the significance of the crack system developed in the test sections by the hydraulic fatigue test.

Conclusions - see [illegible] Report [illegible]
At least a statement is required [illegible]
is this Report [illegible]?

SUMMARY

Test sections were machined from 75mm. and 76mm. gun tubes which were centrifugally cast and coldworked at Watertown Arsenal. These sections

were subjected to hydraulic fatigue tests in which the internal pressure ranged from 13,275 psi to 61,500 psi, and the life ranged from 300 cycles to 20,000 cycles. It was found that,

1. In connection with resistance to progressive stress damage,

a. the life was lineally proportional to the yield strength of the steel as measured before coldwork in the range tested which was 85,000 to 150,000 psi,

b. coldworking improved the resistance to progressive stress damage as compared with noncoldworked gun tubes; the minimum improvement was at least 35 percent in the worst case of high strength steel which was coldworked an insufficient amount to cause yielding throughout the wall thickness; coldworked to strength centrifugal castings were consistently superior to heat-treated-to-strength forgings in resistance to progressive stress damage.

c. as the wall ratio increased the equivalent uniaxial stress was decreased for the same internal pressure and life was improved; the "maximum stress" criterion for calculating the equivalent uniaxial stress gave the least dispersion in the data.

d. when compared with smooth bore tubes the life concentration factor due to "French" rifling in these coldworked tubes was found to be 1 (no concentration effect) and that due to "Rib" rifling was found to be 2, these factors being approximately half those observed in heat-treated-to-strength tubes.

e. Proof-firing did not measurably affect the performance of test cylinders in the hydraulic fatigue tests. However, a single cycle of high pressure was found to be beneficial, although the degree of improvement was slight and masked by the scatter in the data. The cracks which form during proof-firing had no marked deleterious effect.

2. In connection with strength of cannon sections, the strength of coldworked-to-strength sections was consistently materially superior to that of heat-treated-to-strength sections when made of steel of the same strength; when sections of equal dimensions were compared, the strength of those requiring extensive removal of metal from the outside of the coldworked tube tended to be less than the strength of the sections requiring little metal to be removed, although the effect was slight and nonuniform; the maximum observed range in strength data was 16% which is a reasonably small variation for tubes which are representative of wartime production involving not only

well-established products, but also very new products; in the case of well-established products, the strength was found to range from 5.1% high to 4.4% low of the expected strength based on theory for coldworking tubes made of steel which does not strain harden; in the case of new products the strength was as much as 10% lower than expected when the tube had no recorded history and 4% lower than expected when the recorded history revealed that the tube had been coldworked by an amount insufficient to cause yielding throughout the cross-section, and as much as 4% high when the recorded history revealed no questionable processing; about 77% of the data were above the expected strength based on theory; the strength of the sections was found to be 20% less than that indicated by the so-called 6% coldwork curve used in design. This ~~being~~ a serious discrepancy.

3. There are given, for use by engineers, not only curves suitable for design showing the normal life to be expected of coldworked-to-strength cylinders which are made of steel of any yield strength up to 150,000 psi and which have either no rifling, "French" rifling, or "Rib" rifling, but also, examples on the use of such curves.

4. In connection with the elastic modulus, there was found during strength determinations no measurable evidence of frictional end restraint at packings or other effects which might indicate an apparent modulus of elasticity of steel different from the nominal value of 30,000,000 psi.

5. In connection with the crack system, considerable scatter was observed in the data pertaining to the depth to which the crack could propagate before failure in shear occurred, but a conservative estimate could be made of this depth by a formula involving tensile strength of the steel, bore diameter, wall ratio and internal pressure; many cracks were found in all cylinders but failure always occurred by one crack growing faster than any other; andit follows that if any field tests are undertaken to locate and determine the depth of cracks in cannon in order to evaluate the safety of the weapon, complete coverage of the bore must be made in order to find the single potentially dangerous deep crack even though many cracks are found in the same neighborhood; the major crack system was associated with groove fillets from where the cracks initially propagated in a direction which was not radial as in heat-treated-to-strength sections, but which was at an angle to the radius line and sloping under the grooves; at a later period in the propagation of the crack the direction became radial; all of the coldworked-to-strength sections failed with evidence of ductility, the more ductile appearance at failure was obtained when the wall ratio tended to be large, the internal pressure low and when the steel had high impact resistance.

The study of progressive stress damage is continuing so that the interpretation of the experimental facts may be changed at a later time.

Donald H Newhall

Donald H. Newhall
Capt., Ord. Dept. Res.

APPROVED:

Peter R Kosting

Peter R. Kosting
Metallurgist

J. L. MARTIN
Director of Laboratory

NOTE:-This form is to be executed to show proposed distribution, and forwarded in triplicate to the Chief of Ordnance for prior approval of all distributions. Proposed distribution to agencies or individuals whose official interest in the report is not obvious must be justified by explanatory statements on the back of this form.

BINDING AREA FORM NO. ORDBE-342L. (Rev.) 2 Sept. 1947 *BINDING AREA*

COPIES PREPARED [illegible]

EXTRA COPIES REMAINING [illegible]

WATERTOWN ARSENAL
TECHNICAL REPORT DISTRIBUTION

REPORT NO. [illegible] TITLE: "Progressive Stress Damage and Strength of Centrifugally Cast Cold-worked Gun Tubes"

RESTRICTED

TO:	NO. OF COPIES	DATE OCO APPROVAL	
WATERTOWN ARSENAL-ORDBE			
Laboratory File	1		
Author: [illegible]	[illegible]		
OFFICE, CHIEF OF ORDNANCE			
ORDIR-Artillery	[illegible]		
ORDIM-Ammunition	[illegible]		
ORDIT-Automotive	[illegible]		
ORDIS-Small Arms			
ORDTB-Resl. & Materials	[illegible]		
ORDTM-Ammunition Dev.	[illegible]		
ORDTR-Artillery Dev.	[illegible]		
ORDTS-Small Arms Dev.	[illegible]		
ORDTT-Tank Automotive			
ORDTU-Rocket Dev.	[illegible]		
ORDTX-Executive			
ORDTX-AR - Executive Library	1		
ORDNANCE DEPARTMENT AGENCIES			
ORDBA-Frankford Arsenal	[illegible]		
ORDBB-Picatinny Arsenal			
ORDBC-Rock Island Arsenal	[illegible]		
ORDBD-Springfield Armory	[illegible]		
ORDBF-Watervliet Arsenal	[illegible]		
ORDBG-Aberdeen Prov. Ground	[illegible]		
ORDJR-Raritan Arsenal			
ORDMX-Detroit Arsenal			
ORDTZ-Aberdeen Prv. Gr.-R.& D. Ctr.	[illegible]		
WATERTOWN ARSENAL:			
Applied Mechanics Branch	[illegible]		
Ferrous Metallurgy Branch	[illegible]		
Physical Testing Branch	[illegible]		

OTHER:	NO. OF COPIES	DATE OCO APPROVAL	DATE SENT
Navy Dept.-Bur. of Ordnance	[illegible]		
Office of Naval Research	[illegible]		

APPROVING AUTHORITY:

Ltr.:

Date:

From:

INTRODUCTION

The development of light weight gun tubes during World War II resulted in the use of cannon sensitive to progressive stress damage[1]. Typical examples are the 76mm. M1 and the 75mm. M5 guns. The latter gun is withdrawn from service before the extent of erosion has ruined the ballistic characteristics. In contrast, conventionally designed tubes of heavier proportions are withdrawn from service because of erosion[2].

The light weight gun barrels were first manufactured from heat-treated-to-strength tubes. The results of firing tests revealed the need for adding toughness tests to the specification[3] for the steel. In the coldwork process of manufacture of gun tubes the strength of the steel which is required is less than that used in the heat-treated-to-strength manufacturing process. The initial toughness of the steel is therefore potentially higher and, in addition, compressive stresses are present at the bore surface. Both of these factors should contribute to better resistance to progressive stress damage.

During World war II several thousand 76mm. M1A2 tubes were produced from centrifugally cast steel tubes which were heat-treated such that the steel had an actual yield strength of approximately 85,000 psi. The tubes were then coldworked 6 percent to strength. As far as is known none failed from progressive stress-damage.

The 75mm. aircraft cannon are more highly stressed than the 76mm. cannon. The centrifugally cast tubes produced at Watertown Arsenal for this gun were initially heat-treated-to-strength. Toward the end of the war a production experimental program[4] was initiated at the Arsenal in the first part of which a group of ten 75mm. aircraft cannon tubes were prepared as an experimental order. All were centrifugally cast and then were subdivided into four groups. The tubes were heat-treated such that the steel of three tubes in one group had a yield strength of approximately 100,000 psi; the steel of three tubes in the second group had a yield strength around 125,000 psi; and the steel of three tubes in the third group had a yield strength of about 150,000 psi. These were then coldworked approximately 2% and then were finished into 75mm. rifled tubes. The tenth tube which formed the fourth group was heat-treated-to-strength; the steel had a yield strength of approximately 150,000 psi. On the basis of initial tests, centrifugally cast high strength coldworked tubes were produced in quantity.

The ~~In this~~ report presents ~~are given~~ the results of the hydraulic fatigue tests of centrifugally cast coldworked 75 and 76mm. gun tubes made of steel ~~at each of the strength~~

1. "Progressive Stress Damage": P. R. Kosting - Surface Stressing of Metals, Chapter V, A.S.M., 1946, Cleveland, Ohio and WAL Report 731/170, 21 August 1945.
2. "Evaluation of Erosion and Damage in Cannon Bores": TB9-1860-2, 29 November 1945.
3. Specification 57-106A - "Steel Forgings for Cannon Tubes", 1 January 1945.
4. Memorandum to Production Manager at Watertown Arsenal from Capt. D. H. Newhall, 30 October 1944, in connection with Exorder G-2164, 8 July 1944, covering cost of manufacture of experimental gun tubes 75mm., M5A2.

from page 6

~~levels mentioned in the previous paragraphs~~. In order to obtain data which the engineer could use in designing[5] for resistance to progressive stress damage, test cylinders with wall ratio ranging from 1.2 to 1.8 were used. In the preparation of the test cylinders considerable metal was removed from the outside surface of the coldworked rifled tube. The yield strength ~~pressure~~ of some of these test cylinders was therefore measured in order to determine the influence of the removal of the coldworked metal upon strength. The slope of the elastic expansion curve of the cylinders was also calculated and compared with the theoretical one based on 30,000,000 psi as being the value for Young's modulus.

The resistance to progressive stress damage of the coldworked tubes was compared with that of heat-treated-to-strength centrifugal castings and forgings in order to evaluate the benefit of coldworking.

TEST PROCEDURE

A. Yield Strength Pressure Determination

In many instances, prior to the application of repeated loads, the yield strength pressure of the tube section was determined. The pressure was applied in small increments and the strain on the outside of the section was measured with Baldwin-Southwark SR-4 strain gages and a strain indicator. This technique involves the determination of yielding at the bore interface in a "reflected" measurement on the outside surface.

When the metal at the bore interface has just reached the yield point, a very small amount of plastic deformation has occurred at the bore interface, but the remaining section is still an elastic body. The ratio of strain on the outside to that on the inside, for all practical purposes, still follows Hooke's law for elastic deformations. The evaluation of yielding at the bore was based on this concept. Since the yield strength of the steel, as determined by the tensile test, was obtained at .01% offset, the yield at the bore of the cylinder was determined at .01% offset also. At the bore .01% offset is 100 millionths of an inch per inch offset. From the Lamé strain equations applicable to elastic thick hollow smooth bore[6] cylinders without end restraint, the following relation was derived for e_o (0.01), the offset on the outside equivalent to .01% offset at the bore,

$$e_o\,(0.01) = \frac{.0002}{.7 + 1.3w^2} \quad \text{or \% offset on O.D. } (0.01) = \frac{.02}{.7 + 1.3w^2}$$

in which w = wall ratio = O.D./I.D.**. Poisson's ratio was used as 0.3. Fig. 1 is a graph showing the percent offset on the outside diameter equivalent to

---

5. Up to the start of World War II cannon were designed on the basis of strength only.
6. Watertown Arsenal Gun Division Report WGD-4: "Selected Design Data Pertaining to Gun Tubes and High Pressure Vessels": By D. H. Newhall, 6 December 1943.

** O.D. = Outside Diameter; I.D. = Inside Diameter

.01% offset on the inside diameter of a tube section as a function of wall ratio. Fig. 2 is a typical illustration of a yield strength determination sometimes referred to as elastic strength. Also shown is the calculation of the slope of the curve and of Young's Modulus based on the slope and wall ratio.

B. Hydraulic Fatigue Test

With the equipment developed, it was possible to introduce repeatedly hydraulic pressure to the bore of cannon sections at a rate of approximately six cycles per minute. The magnitude of the pressure was similar to that normally used in guns, ranging as high as 61,500 psi. A detailed description of the equipment and controls is appended to this report*. The high pressure was controlled within 200 psi. When the pressure was fully released, the residual pressure was less than 1000 psi. Electric SR4 strain gages and strain measuring and recording equipment were used to determine some of the elastic properties of the tube sections during the test, the strain developed on the outside of the tube sections being recorded with each cycle of pressure. Typical extracts from the continuous records for Cylinder D12 are shown in Fig. 3. Cylinders were usually tested until failure occurred at which time they could no longer hold pressure because of fissuring or rupturing. In some cases, however, specimens were removed from test before failure because of one of the following reasons (1) failure was imminent, as revealed by plastic distortion occurring on the outside surface, (2) the number of cycles was very large and further test to failure was not considered necessary at the time; (3) a large overshoot of pressure occurred and further testing was stopped.

C. Specimens

The proportions of the test cylinders were selected on the basis of the results of a study[7] of the extent and depth of progressive stress damage cracks developed in a rather long specimen. The minimum length of cylinders for the caliber sizes 75mm. and 76mm. was judged to be 12½". A detailed drawing of the test specimen is shown in Fig. 16 of Appendix A. Gun tubes were sectioned and turned to the desired wall ratio which was based on groove diameter. Metal was allocated for tensile and Charpy impact tests of the steel at various positions along the length of the tube, as shown in a typical layout of the gun tubes on Fig. 16 of Appendix A. In this figure also is indicated the numbering system; code letters, A, B, C, etc. were used to identify tubes and numerals 2, 3, 4, etc. to identify cylinders from these tubes.

D. Progressive Stress Damage

Progressive stress damage was evaluated (1) by noting the number of cycles to failure, (2) by examination of the fissure and fracture, and (3) by measuring the depth and distribution of cracks. For the latter purpose a section for macroetching

* See Appendix A.

7. "Progressive Stress Damage Through Repeated Applications of Hydraulic Pressure": J. B. Cohen, WAL Report 731/101, 2 May 1944.

was cut in the zone of maximum damage, as revealed either by examination of the fracture or by determining where bulging was most extensive. The change in outside diameter was used as a measure of the extent of bulging.

E. Test Metal

Cylinders from the following cannon were subjected to hydraulic fatigue tests.

1. Four 76mm. centrifugally cast, coldworked-to-strength and rifled tubes A, B, C and D of which B and C were proof-fired.

2. Three 75mm. (anti-aircraft) centrifugally cast, coldworked-to-strength and rifled Tubes E, F and G.

3. One 75mm. (anti-aircraft) centrifugally cast heat-treated-to-strength and rifled tube N.

4. One 76mm. centrifugally cast and coldworked-to-strength, smooth bore tube I.

5. One 75mm. centrifugally cast and coldworked-to-strength, smooth bore tube K.

Details concerning the metallurgical history and physical properties of the steel of each tube are given in the Data Sheets in Appendix B.

Tubes A, B, C, D and I were all manufactured in the same manner with well-established production procedures and were not produced under special laboratory control. The physical properties of the steels were approximately identical and these data were considered comparable. The average yield strength (0.01% offset) of the steels before coldwork was 87,155 psi. Tubes B and C were proof-fired; the other tubes were not. Tubes A, B, C and D were rifled but Tube I was smooth bore.

In contrast to these tubes of steel having approximately 87,000 psi yield strength before coldwork, other tubes, E, F, G, K and N were made of steel with different yield strength levels. The yield strengths before coldwork were:

Tube E - 100,500 psi
Tube F - 121,850 psi
Tube G - 151,700 psi
Tube K - 125,000 psi
Tube N - 159,300 psi

They differed in other respects also. They were the first of a new product processed with makeshift containers, etc. The E, F and G tubes had the "French" form of rifling (Dwg. C7226893), whereas the A, B, C and D group had the conventional rib rifling (Dwg. 15-OKD-2). Tube K was smooth bore. The

A, B, C, D and I group was 76mm. in caliber (3.00"), while the E, F, G, K and N group consisted of 75mm. tubes (2.95") for aircraft cannon. They also differed in the amount of coldworking. The A, B, C, D and I group was processed with the conventional 6% coldwork, while the E, F and K group was coldworked nominally 2%, and the G tube was coldworked 1.1%. The actual percent coldwork for each tube is given in Appendix B. The one tube "N" was not coldworked but was heat-treated-to-strength. These data are summarized in Table I.

RESULTS

The results of the hydraulic fatigue tests and of the examination of the fracture after testing are given in Tables II and III. In these tables are given the cylinder number; the wall ratio; the maximum internal pressure which was applied during the determination of strength prior to fatiguing; the yield strength pressure, also referred to as the elastic strength pressure, at which the offset at the bore was 0.01%; the internal pressure during the fatigue test; the equivalent uniaxial stress; the life in cycles to failure by fissuring except as indicated; the maximum depth of remaining cracks, i.e., cracks other than the one which penetrated the full wall thickness; the bulge, as measured by the maximum change in outside diameter; the wall thickness of the tube at point of failure, the wall thickness before test being listed in Table IV of Appendix A; the depths from bore interface to base of Zone 1 in the fracture where the texture was fine, Zone 2 where the direction of the crack started to change, Zone 3 where the change in direction was completed and the direction became radial, Zone 4 where failure in shear occurred. The details of the study of the fissure, fractures and cracks are given in Appendix C. The crack study of the tubes listed in Table III was not as detailed as that of the tubes listed in Table II and therefore depths of all zones are not tabulated.

The following curves were derived from these data:

a. Hydraulic Fatigue Test Results - A, B, C, D Tubes in Terms of Equivalent Uniaxial Stress, as Calculated by,

    1. Maximum stress description
    2. Von Mises description - Fig. 4

b. Relationship Between Equivalent Uniaxial Stress (Maximum Stress Description) and Number of Cycles to Failure in Hydraulic Fatigue Tests - Fig. 5

c. Relationship Between Internal Pressure and Cycles to Failure as Influenced by Wall Ratio and Rifling for A, B, C, D and I Tubes - Fig. 6

d. Relationship Between Internal Pressure and Cycles to Failure for E, F, G and N Tubes (Wall Ratio - 1.57) - Fig. 7

e. Elastic Strength of Cannon Sections After Coldworking, Soaking at 570°F and Machining, Including Rifling for Tubes A, B, C, D and I and Heat-treated-to-Strength Tube N - Fig. 8

f. Study of Elastic Modulus - Fig. 9

g. Equivalent Uniaxial Stress to Cause Failure at 10,000 Cycles as a Function of Yield Strength of Coldworked-to-Strength and of Heat-treated-to-Strength Tubes - Fig. 10

h. Equivalent Uniaxial Stress to Cause Failure at 10,000 Cycles as a Function of Yield Strength of Coldworked-to-Strength Tubes - Fig. 11

i. Influence of Yield Strength Before Coldworking (0.01% offset) on the Relationship of Equivalent Uniaxial Stress (Maximum Stress Description) and Cycles to Failure for,

   1. Rib rifling - Fig. 12
   2. French rifling and Smooth bore - Fig. 13

DISCUSSION

Stress-Cycle Curves

The presence of a bi-axial (combined) stress in cannon makes it necessary to correlate the response of cannon to a stress system in terms of an equivalent uniaxial stress since by far most physical data are obtained from tensile test specimens nominally under a uniaxial stress system. The various theories[6] of yielding describe combined stresses in terms of an equivalent uniaxial stress. The most usable description of the equivalent uniaxial stress for rupture in fatigue is the one which will yield a relation in the stress cycle (S-N) plane which is indeoendent of wall ratio. Five conventional methods of combining stresses were investigated. They were maximum shear, constant energy of distortion, strain energy, maximum strain and maximum stress. Typical curves for (a) maximum stress description and (b) the constant energy of distortion (Von Mises) description are shown in Fig. 4. It was found that the maximum stress theory applied to these data resulted in the least amount of scatter in the S-N plane and the data indicated a linear relation between Log S and Log N. This would indicate that the tangential stress component of the combined stress predominated in development of progressive stress damage in these specimens. A possible explanation for this may be found in the relatively small radial stress existing due to the proportions of the cylinders studied. The cracks originate at the groove fillets. These re-entrant corners are unfavorably

oriented in the applied tension field and made the tangential stress component predominate still more. Once a fissure is developed at the bore interface, the ratio of the radial stress to the tangential stress at the bottom of the fissure should become negligible.

Fig. 5 shows the observed data in terms of the equivalent uniaxial stress calculated by the maximum stress description. The derivation of formulae relating the various theories of yielding in uncapped, thick, hollow cylinders uses the term "Pressure Factor". Pressure factor is a dimensionless quantity and is the ratio of internal pressure in the cylinder at which yielding occurs to the yield strength of the steel. When used to describe an equivalent uniaxial stress, the pressure factor may be regarded as the ratio of internal pressure to the equivalent uniaxial stress caused by that internal pressure.

While the number of observed points was few in the case of the E, F, G, I and K tubes, as compared to the A, B, C and D tubes, there are many similarities in the data indicating that the observations are reliable. The curves for the E, F, G, I and K tubes in the S-N plane have the same slope as the A, B, C and D tubes, but are displaced by an amount dependent upon rifling and the yield strength of the steel before coldwork. Since Tube I was smooth bore and had no stress raisers due to rib rifling with small fillets, the cylinders from it lasted longer than those from tubes A, B, C and D. The ratio of the life of smooth bore cylinders to that of rib-rifled cylinders was 2. This compares with 4.2 for heat-treated-to-strength[8] tubes. The performance of cylinders from Tube I was found to be duplicated by cylinders from a tube of similar history and properties and therefore this life concentration factor of 2 for rib rifling in coldworked, centrifugally cast tubes is considered to be reliable.

The smooth bore cylinders from Tube K of intermediate strength had the same life as the cylinders having French rifling with generous fillets. The ratio of life of smooth bore to that of French-rifled cylinders therefore was 1, which compares with 2.4 for heat-treated-to-strength tubes[8]. However, in the section of this report dealing with yield strength, it is shown that the K10 cylinder from the K tube was not as relatively strong as the cylinders from the other coldworked tube. Therefore, assuming at the worst that the whole tube was weaker than normal, then the life of cylinders from the tube would be shorter than normal. The estimated correction for the short life due to possible low strength is 20% so that the life concentration factor for French rifling in coldworked, centrifugally cast tubes may be between 1.0 and 1.2. Since the variation from nominal strength of the K cylinder was 10% and the variation in strength of the cylinders from the other tubes ranged through 9.5%, it may be that this concentration factor is nearer to 1.0, as observed, than to 1.2.

The factors of 2 and 1 indicate that in coldworked, centrifugally cast tubes the life concentration factor due to rifling is about one-half of the life concentration factor due to rifling in heat-treated-to-strength forged tubes. This

8. "Preliminary Investigation of the Effect of Rifling, Strength of Steel, Chromium Plating and Nitriding on Progressive Stress Damage of 75mm. M5A1, M6 and M10 Gun Sections": P. R. Kosting, 1948, WAL Report No. 731/293.

benefit may be attributed to the compressive stresses at the bore. The extent of the benefit to be attributed to the lack of directionality of properties in castings, as compared to forgings, is under study.

The slope of the curves for coldworked tubes in Fig. 5 is considered to be reliable for the range in life that was investigated. Involved are nine heats of induction furnace melted steel. The slope is less than that for heat-treated-to-strength tubes. This was also found to be true for forgings[9]. The slope of the S-N curves for coldworked, centrifugally cast cylinders is -0.185. The curve for heat-treated-to-strength centrifugally cast cylinders has a slope of -.281. This latter is very close to -.27 as previously reported for heat-treated-to-strength forgings.

There are six instances where paired cylinders were tested, one of the pair being subjected to a single cycle of high internal pressure and the other not being subjected to this high pressure prior to test. In all cases the former had a longer life than the latter, although the improvement in life was not greater than the general scatter in all the data.

It was not possible to distinguish between performance of cylinders from proof-fired tubes B and C and that of cylinders from nonproof-fired tubes A and B. This may be because most of the cylinders from the A, B, C, D, I and N tubes were subjected before the fatigue test to one cycle of high pressure during the determination of the yield pressure. Such a procedure is somewhat similar to proof-firing during inspection of cannon. The data therefore show that proof-firing is not deleterious to resistance to progressive stress-damage in the hydraulic fatigue test and suggest that proof-firing may be beneficial in that it might improve slightly the resistance to progressive stress damage. The cracks which formed during proof-firing have no marked deleterious effect, probably because of the compressive stress system. Study is under way to evaluate directly the influence of heat checking such as is encountered during proof-firing and then developed further during the initial stages of field service.

The Charpy impact resistance indicate that the steel in Tube N was not as well quenched out prior to tempering as was the steel in the E, F and G tubes, otherwise the N tube was comparable to the G tube, especially with regard to tensile strength, ductility and impact resistance after coldwork. The stress-cycle curve for the N tube is shown in Fig. 5. It should be pointed out, however, that this curve was established with few observed points in a narrow range of stress. The difference in life between N and G is greater than can be accounted for by the difference in yield strength of the steels in the condition in which they are subjected to test. The residual stresses due to coldworking are, therefore, considered to be

---

9. "Cannon Tubes - Progressive Stress Damage In - Hydraulic Fatigue Test of Forged, Coldworked-to-Strength 90mm, Rifled Tube J and Forged, Heat-treated-to-strength 90mm, Rifled Tubes S and U"; Robert W. Freeman and Francis W. Cotter, 1947, WAL Report No. 731/199-2(R).

appreciably beneficial to an extent that is at least 35 percent in resisting progressive stress damage. Recent experiments in progress show that without the complicating factor of strengthening of the steel due to cold-work, compressive stresses at the bore improve life as much as these figures indicate.

Pressure Cycle Curves

Figs. 6 and 7 are curves derived from the equivalent uniaxial stress cycle relation shown in Fig. 5. Inasmuch as the relationship was linear, the conversion of the data to the pressure-cycle-wall ratio relationship was readily made. If Sn is the equivalent uniaxial stress (maximum stress description) to cause failure at a particular number of cycles, then the internal pressure "IP" that would rupture a cylinder with a wall ratio (W) in the same number of cycles would be,

$$IP = Sn \frac{W^2-1}{W^2+1} \cdots$$

Thus, when Sn equals 130,000 psi for the A, B, C and D tubes for a cylinder having a wall ratio of 1.5, the internal pressure to have a life of 1,000 cycles would be IP = 50,000 psi, and for a wall ratio of 1.2, IP = 23,400 psi. Superimposed on these curves are the observed points. The total range in cycles for life, namely, roughly 1,000 to 20,000, is rather limited, especially for thin tubes and should be extended further.

Yield Strength Pressure

A summation of the data concerning the yield strength pressure of the cylinders is shown in Fig. 8.

Curve B is the theoretical strength in accordance with yielding by the Von Mises' concept in terms of pressure factor and wall ratio. In the derivation of this curve it was assumed that the cylinders were free to expand or contract longitudinally. This curve is applicable to only those tubes which have not been overstrained; that is, heat-treated-to-strength tubes and not coldworked-to-strength tubes. There is an apparent agreement with the observed points from the "N" tube except for very small wall ratios where the relative error in all measurements of both pressure and strain is greatest.

From the theory of plasticity, wherein it is assumed that the material in the cylinder does not strain harden, a mathematical relation for the pressure needed to place the metal throughout the wall into the plastic state is given[10] by,

$$\frac{IP}{Syp} = \frac{2}{\sqrt{3}} \ln W$$

10. "Calculation of Pressure Expansion Curves of Circular Cylinders": R. Beeuwkes, Jr. and J. H. Laning, Jr., WAL Report No. 730/111, 1944.

when the Von Mises' concept is used to describe initial yielding, where IP = internal pressure at yielding; Syp = yield point stress (stress at which a tensile bar of this hypothetical material would change abruptly from the elastic to plastic state), and Ln W is the natural logarithm of the wall ratio. Curve A in Fig. 8 is the plot of this equation. The observed yield strength pressure for the cylinders from the coldworked tubes, in terms of pressure factor $\frac{IP}{Sy(.01)}$ where Sy(.01) is the yield strength (0.01% offset) of the steel, are also shown. This curve applies for values of yield strength of steel before coldworking up to and including 150,000 psi and all amounts of after coldwork machining that would probably be encountered, providing sufficient coldworking is done to assure plastic flow throughout the wall. The range in scatter of test results was about 16%. This is a reasonably small variation for gun tubes which are representative of wartime production. The data for the high strength tube G were below the curve by 4 percent. However, this tube was coldworked only 1.1 percent. Had it been coldworked 2 percent or more as were the others it would have been stronger. The data for the E and F tubes which are considered normal products are above the curve by as much as 4.3 percent. These data also reveal that coldworking only 2% does affect the strength of the tube after final machining disproving belief to the contrary[11].

The data for this smooth bore tube K of intermediate strength were 10 percent below the curve for which no reason is apparent from the incomplete history of the tube. The coldwork record of the tube is lost and therefore the actual percent coldwork is not now known. The tensile strength data confirm that the tube was coldworked as does the high value of the calculated pressure factor relative to that expected for heat-treated-to-strength tubes. However, only one K cylinder was tested for strength. In the A, B, C and D tubes, representative of well-established production practices, at wall ratios of 1.6 and 1.8, the range in data was 5.1% high and 4.4% low. This indicates that the scatter ranged through 9.5% and that strength determinations of several cylinders are necessary in order to determine the average performance. About 77% of the data pertaining to curve "A" are above the curve and only 16% are below it, indicating that this curve is on the conservative side. The old equation[6] used in connection with the coldwork process was,

$$\frac{IP}{YS} = \mathrm{Ln}\ W$$

and such a curve would be very conservative.

The 6 percent design curve[6] used in design* is roughly 20 percent higher than curve A in Fig. 8. This is a serious discrepancy. The machining off of large amounts of excess metal from some of the cylinders

11. "History of the Production of Centrifugally Cast Gun Tubes with High Impact Resistance": John F. Wallace, WAPD Report WDG-17, 17 October 1946.

* See also "Data for Calculating Pressure for Coldworking Cylinders 6%" in Watertown Arsenal Experimental Report #363, T. C. Dickson, 1 February 1932.

did not affect the strength enough to account for this discrepancy. The probable explanation is the high sensitivity of the strain measuring equipment compared to that used in General Dickson's time. This would detect yielding at lower pressures. Pressure measuring techniques were also better. Furthermore, the data might indicate that (1) no strain hardening of the steel can be counted on, (2) all that is necessary to obtain strengthening by coldworking is to be sure that the tube is plastically deformed throughout the section, and (3) further coldworking adds little to the strength. This subject is to be studied further.

The problem of design of coldworked cannon from the point of view of strength is complicated by the machining after coldworking and the different plastic properties (strain hardening characteristics) of steel at different yield strength levels. The machining and rifling after coldworking alters the distribution of residual stress and removes the most highly overstrained material. In conventionally designed cannon tubes, where a relatively large factor of safety is used, and where the working stress is relatively low, a small error in estimating the strength of the tube is relatively inconsequential. In the future the margin for error will get less. In correlating with strength the amount of machining on the outside surface of the specimens used in these tests, nonuniform behavior was observed, although the trend was for the strength to be less the more the amount of machining on the outside surface. In two critical experiments, when the amounts of metal removed to get cylinders of the same size was 8.7 and 23.4 sq.in. in the cross section, the lowering of strength was 0 percent in one of the experiments and 3 percent in the other. Far greater amounts of machining after coldwork were done on these specimens than normally was done in the production of coldworked tubes in World War II.

Elastic Modulus

In some of the early coldwork development reports it was indicated that the modulus of elasticity was diminished (as much as 30%) by the coldworking. There was also the possibility that the assumption of no end restraint might not be justified due to the capping effect resulting from the friction of the hydraulic packings. Any change in modulus or friction effects would be reflected in a change of the slope of the elastic portion of the pressure expansion curve, as in Fig. 2. In Fig. 9 is shown the theoretical curve for uncapped cylinders using the modulus of elasticity as 30,000,000 psi and plotting elastic slope vs. wall ratio. The observed slopes are shown in comparison. It would appear there was no change in modulus as expected, or little, if any, effect from frictional end restraint. It is to be noted that the agreement of the elastic strength of the heat-treated-to-strength N tube with the Von Mises' concept further indicates that the end restraint due to packings is negligible.

Design Curves for Coldworked Cannon

In preparing a design stress-life curve for coldworked cannon it was necessary to make several assumptions. The first was that the toughness

of the steel as measured by impact resistance before coldwork would always be reasonably good and there would be no reason to consider its effect on life of the coldwork sections. This was observed to be reasonable on inspection of the test results of the A, B, C and D tubes made of steel which varied in Charpy impact resistance at room temperature from 16 to 75 ft-lbs. The second assumption was that 2% and 6% coldwork would have the same effect on fatigue life. It was shown earlier in this report that sections from both 2% and 6% coldworked tubes had the same strength relationship and thus might have the same life relationship. The last assumption was that the effect of the standard rib rifling stress concentration and the "French" rifling stress concentration combined with the residual stresses at the bore, could be differentiated. It has been shown that the life concentration factors due to these stress raisers were only 2 and 1 in the coldworked, centrifugally cast tubes.

With the assumptions given it was possible to construct curves showing the relationship between the equivalent uniaxial stress (maximum stress theory) for a life of 10,000 cycles and yield strength 0.01% offset of the centrifugally cast steel before coldworking. The curve for smooth bore tubes (encircled dots) and French rifled tubes (black dots), based on the performance of Tubes E, F, G, I and K (marked "cc" for centrifugal casting) as revealed in Fig. 5, is shown to the top of Fig. 10. The curve for Rib rifled tubes (triangles) is the lower one in Fig. 10 and is shown parallel to the curve for French rifled tubes. The reason for the parallelism is based on the data shown in Fig. 11, where the two curves in Fig. 10 appear toward the top under the heading "coldworked to strength". The data[8] for heat-treated-to-strength tubes T, R, M, S, U, W and 3, all made from forgings (marked "f") are shown to the bottom right under "heat-treated-to-strength". These tubes had rib rifling (marked with triangles). The scatter in the data is appreciable and the average curve is considered to be the middle curve of the three toward the bottom of Fig. 11. These curves have the same slope as the coldworked-to-strength curves.

Among the curves in the heat-treated-to-strength section is one based on the superior behavior of Tube "2" made from a forging and rifled with French rifling[8]. The forging was made of tough steel having an impact resistance quite superior to that for the centrifugal casting "N" with French rifling. This superiority of "2" to "N" in resistance to progressive stress damage was obtained despite the possible advantage of the casting with no directional variation in mechanical properties.

By contrast, the coldworked-to-strength forging "J", although superior in resistance to hydraulic fatigue to heat-treated-to-strength forgings made of steel of the same strength, is inferior to coldworked-to-strength, centrifugal castings of similar toughness. Since it is known[8]

that forgings show variations in resistance to fatigue depending upon directionality, and it is suspected that centrifugal castings do not*, the difference between the curve through points A, B, C, D and the curve through point J is mainly attributed to the difference in directionality of properties between centrifugal castings and forgings of equivalent heat-treatment.

Based on Fig. 10, the curves on Fig. 12 for centrifugally cast cold-worked-to-strength tubes with rib rifling and the curves on Fig. 13 for centrifugally cast coldworked-to-strength tubes with French rifling or without rifling were derived showing the influence of yield strength of steel before coldworking on the relationship between equivalent uniaxial stress and cycles to failure.

The use of these curves in design is illustrated in the following three examples, where the symbols used are:

Ln = logarithm to the base e (natural logarithm)
W = wall ratio
x = multiply
Y.S. = yield strength
BCW = before coldwork
psi = pounds per square inch
P = internal pressure or maximum powder pressure
P_s = yield strength pressure

*This question is under experimental investigation.

EXAMPLE I

Given:

1. Maximum powder pressure, piezo-electric = 40,000 psi
2. 2% or more coldworked
3. Yield strength before coldwork (BCW) (.01% offset) = 120,000 psi
4. Factor of safety (strength) used by Ordnance Dept. = 1.5
5. Desired minimum resistance to progressive stress damage = 9500 cycles
6. Rib rifling

Find wall ratio necessary.

Elastic Strength Calculations:

From Fig. 8, the yield strength pressure of any given section of a coldworked tube is estimated by,

$$\text{Yield Strength Pressure} = \frac{2}{\sqrt{3}} \text{ Ln } W \text{x} Y.S. \text{ (BCW)}$$

$$\text{Ln } W = \frac{\text{yield strength pressure}}{\frac{2}{\sqrt{3}} \text{ x } Y.S. \text{ (BCW)}}$$

The desired yield strength pressure = 40,000 x 1.5 = 60,000 psi

$$\text{Ln } W = \frac{60,000}{\frac{2}{\sqrt{3}} \text{x } 120,000} = .433 \text{ or } W = 1.54 \text{ minimum wall ratio for strength}$$

Cycles To Failure: (Equivalent Uniaxial Stress Calculation)

$$\text{Equivalent Uniaxial Stress} = P \left(\frac{W^2+1}{W^2-1}\right) = (40,000)\frac{3.37}{1.37} = 98,500 \text{ psi}$$

From Fig. 12 the life at equivalent uniaxial stress of 98.500 psi is approximately 9,700 cycles which satisfies both the strength and fatigue requirements.

EXAMPLE II

Given:

1. 2% or more coldworked
2. Yield strength before coldworked (.01% offset) = 120,000 psi
3. Factor of Safety (strength) used by Ordnance Dept. = 1.5
4. Wall Ratio = 1.6
5. Desired life = 15,000 cycles
6. Rib rifling

Find what maximum powder pressure the gun could safely withstand.

Elastic Strength Calculations:

Yield Strength Pressure = $(P_S) = \frac{2}{\sqrt{3}}$ Ln WxY.S. (BCW)

$$P_s = \frac{2}{\sqrt{3}} (\text{Ln } 1.6)\ (120{,}000)$$
$$= 65{,}000 \text{ psi}$$

The maximum powder pressure = $\frac{65{,}000}{1.5} = 43{,}300$ psi

Cycles to Failure: (Equivalent Uniaxial Stress Calculation)

$$\text{Equivalent Uniaxial Stress} = P\left(\frac{W^2+1}{W^2-1}\right) = 43{,}300\ \left(\frac{3.56}{1.56}\right) = 99{,}000 \text{ psi}$$

From Fig. 12, the life at equivalent uniaxial stress of 99,000 psi is 9,500 cycles which does not satisfy the life requirement.

The equivalent uniaxial stress (Fig. 12) for life of 15,000 cycles is 91,000 psi.

The maximum powder pressure for this equivalent uniaxial stress is as follows:

$$\text{Equivalent Uniaxial Stress} = P\left(\frac{W^2+1}{W^2-1}\right) = 91{,}000 \text{ psi}$$

$$P = (91{,}000)\ \left(\frac{1.56}{3.56}\right) = 39{,}800 \text{ psi}$$

This pressure would satisfy both the strength and fatigue requirements.

EXAMPLE III

Given:

1. Maximum powder pressure, piezo-electric = 40,000 psi
2. 2% or more coldworked
3. Factor of Safety (strength) used by Ordnance Dept. = 1.5
4. Wall Ratio = 1.6
5. Desired life = 15,000 cycles
6. (a) Rib rifling
   (b) French rifling

Find yield strength of steel before coldwork necessary.

Cycles to Failure: (Equivalent Uniaxial Stress Calculations)

$$\text{Equivalent Uniaxial Stress} = P\left(\frac{W^2+1}{W^2-1}\right) = 40{,}000\left(\frac{3.56}{1.56}\right) = 91{,}250 \text{ psi}$$

From Figs. 12 and 13 the yield strength necessary for life of 15,000 cycles at the equivalent uniaxial stress of 91,250 psi would be approximately 121,000 psi if rib rifling is used and 96,000 if French rifling is used.

Elastic Strength Calculations:

$$\text{Yield Strength Pressure} = \frac{2}{\sqrt{3}} \text{Ln } W \times \text{Y.S. (BCW)} = 1.5\ (40{,}000)$$

$$\text{Y.S. (BCW)} = \frac{(1.5)\ (40{,}000)}{\text{Ln } 1.6}\left(\frac{\sqrt{3}}{2}\right)$$

$$= 110{,}000 \text{ psi}$$

(a) To meet the strength requirements, yield strength of 110,000 psi would be necessary. The life expected from Fig. 12 would be approximately 12,000 cycles if rib rifling is used. Therefore, use 121,000 psi yield strength (BCW) material if Rib rifling is to be used.

(b) The life expected from Fig. 13 would be approximately 19,000 cycles. Therefore, use 110,000 psi yield strength (BCW) material if French rifling is to be used.

NOTE: Resistance to erosion should also be considered in choosing between Rib rifling and French rifling.

Crack System

The detailed study of the crack system in the cylinders after test is described in Appendix C. It was shown that initially the cracks tended to grow in a direction that sloped under the grooves. The thinner the tube or the stronger the steel, the less was the tendency for the cracks to slope under the grooves.

Failure of coldworked tubes was in a ductile fashion. The most ductile failures were obtained when the wall ratio tended to be large, the internal pressure low, and when the steel had high impact resistance.

As the test pressure was decreased in groups of cylinders of constant wall ratio, the depth of crack to point of shear prior to instant of failure increased and the number of relatively deep cracks decreased, and the maximum depth of cracks, other than the one which caused failure, decreased.

Failure occurred by one crack growing faster than any other and penetrating the wall thickness of the cylinder. If field tests are developed to locate and determine the depth of cracks in cannon in order to evaluate the safety of the weapon, it will not be adequate to locate a group of cracks, but the single potentially dangerous deep crack will have to be found by a complete survey of the whole bore circumference.

It was found possible to calculate reasonably well the depth to which the crack can grow before failure in shear occurs.

Acknowledgment

The tests which are described in this report were carried out over a long period of time with the assistance of Mr. H. C. Mann, Materials Engineer, Mr. A. R. Kelly, Coldwork Operator Supervisor, Mr. R. W. Freeman, Mechanical Engineer and others. The cooperation of all is gratefully acknowledged.

UNCLASSIFIED U.S. ARMY MATERIALS RESEARCH AGENCY
WATERTOWN, MASSACHUSETTS 02172

TABLE I

Summary of the Characteristics of the Tubes

Tube	Yield Strength of Steel Before Coldwork (0.01% offset) psi	Average Percent Coldwork	Rifling	Caliber in.	
A	88,500	6.0	Rib	3.00	
B	89,250	6.0	Rib	3.00	Proof-fired
C	85,000	5.7	Rib	3.00	Proof-fired
D	85,880	5.2	Rib	3.00	
E	100,500	2.1	French	2.95	
F	121,850	2.3	French	2.95	
G	151,700	1.1	French	2.95	
I	88,250	6.0	None	3.00	
K	125,000	x	None	2.95	
N	159,300	0.	French	2.95	

x = 2% nominal

Why is Gun [illegible] Lower [illegible]
DCW [illegible] Tab III ?

So These are [illegible]

UNCLASSIFIED

Results of Hydraulic Fatigue Test and Examination After Testing of Cylinders From Tubes, A, B, C, and D

Cylinder Number	Wall Ratio O.D./I.D.	Maximum Internal Pressure Prior to Hydraulic Fatigue Test, psi	.01% offset Yield Pressure psi	Test Internal Pressure psi	*Equivalent Uniaxial Stress psi	Life cycles	**Maximum Depth of Remaining Cracks inch	Bulge Δ diameter inch
C-10	1.2	18,000	18,000	19,000	105,000	3997	.18	.069
B-12	1.2	17,875	18,000	17,200	95,500	3413	—	.246
A-12	1.2	20,500	20,500	16,800	93,000	1150	—	.069
C-11	1.2	19,000	18,750	16,500	91,500	(10401 NFI)	(.12 NFI)	.019
C-12	1.2	18,275	18,500	13,275	73,500	(20322 NF)	(.025 NF)	.003
A-11	1.3	31,000	28,500	31,900	124,200	1015	--	.324
B-2	1.3	28,000	27,000	26,750	104,500	1629	—	.318
A-2	1.3	27,000	27,750	23,600	93,000	8291	—	--
B-11	1.3	27,000	27,000	22,600	88,000	5532	—	.075
A-10	1.4	39,000	38,000	39,050	121,000	2665	—	.207
C-6	1.4	34,750	34,000	34,750	107,200	2662	.051	.211
C-9	1.4	34,500	33,500	32,000	99,200	5002	.135	.152
B-10	1.4	34,500	34,500	31,350	97,000	4724	—	.181
C-8	1.4	33,750	34,000	28,750	89,000	6438	.13	.087
D-12	1.4	35,500	35,000	27,500	85,000	12629	.17	.038
A-9	1.5	48,000	47,000	48,350	125,500	1141	—	.295
B-9	1.5	43,000	42,000	40,100	104,200	3732	—	.156
A-8	1.6	56,250	--	56,750	--	(798 NF)	(.40 NF)	.222
B-8	1.6	51,000	49,000	48,400	110,000	3717	--	.111
B-5	1.6	48,000	45,000	48,000	109,000	2335	.13	.362
C-2	1.6	48,000	45,000	48,000	109,000	2637	.13	.222
B-6	1.6	49,750	47,500	47,250	107,500	3409	.185	.128
C-5	1.6	49,500	47,000	47,000	106,800	2923	.18	.162
C-4	1.6	49,000	46,000	46,500	105,500	2950	.16	.236
A-5	1.6	49,500	48,000	44,500	101,300	3058	—	.080
C-3	1.6	49,000	47,500	44,000	100,000	4342	.25	.194
D-11	1.6	49,000	48,000	44,000	100,000	4298	.22	.236
B-4	1.6	48,500	45,000	43,500	99,000	4175	.275	.177
D-9	1.6	48,250	47,500	38,250	87,000	6495	.45	.061
B-10	1.6	48,750	46,500	36,250	82,500	9842	.44	.097
A-6	1.7	65,000	58,000	58,850	121,000	2830	—	--
D-4	1.8	62,500	59,500	61,500	116,500	3150	.21	.432
D-3	1.8	--	—	59,000	[illegible]	3086	.21	.439
D-2	1.8	61,500	57,500	59,000	111,000	3486	.21	.221
D-5	1.8	—	—	48,500	91,500	7520	.59	.475
D-6	1.8	—	--	48,500	91,500	(5385 NF)	(.06 NF)	.007
D-8	1.8	63,500	60,000	48,500	91,500	10863	.51	.059
B-3	1.8	60,000	56,000	48,500	91,500	6998	.54	--
A-3	1.8	--	--	48,500	91,500	6636	.52	--

NF = did not fail - removed from test before fissuring
NFI = did not fail but fissuring was imminent
x = Fracture where texture was fine
xx = Where direction of crack starts to change
xxx = Where change in direction was completed
xxxx = Where failure in shear occurred.

*Maximum stress desc
**Disregarding point
***Deepest crack
****Zone 5

A

*Equivalent Uniaxial Stress psi	Life cycles	**Maximum Depth of Remaining Cracks inch	Bulge Δ diameter inch	Wall**** Thickness At Fissure After Test inch	Depth from Bore Surface, Inch Zone 1 x inch	Zone 2 xx inch	Zone 3 xxx inch	Zone 4 xxxx inch
105,000	3997	.18	.069	.30	.08	.12	.13	.18
95,500	3413	--	.246	.26	.06	.06	.10	.20
93,000	1150	--	.069	--	.02	.10	--	--
91,500	(10401 NF)	(.12 NF)	.19	--	.06	.08	.10	(.22)***
73,500	(20322 NF)	(.025 NF)	.003	--	--	--	--	--
124,200	1015	--	.324	--	.01	.05	--	--
104,500	1629	--	.318	.30	.06	.06	.10	.25
93,000	8291	--	--	--	.08	.08	.18	.33
88,000	5532	--	.075	--	.10	.10	--	.33
121,000	2665	--	.207	--	.06	--	--	.29
107,200	2662	.051	.211	.52	.06	.11	.18	.28
99,200	5002	.135	.152	.50	.06	.12	.18	.42
97,000	4724	--	.181	.58	.08	.16	.18	.26
89,000	6438	.13	.087	.53	.08	.16	.25	.35
85,000	12629	.17	.038	.52	.22	.22	.28	.45
125,500	1141	--	.295	--	.07	--	--	.35
104,200	3732	--	.156	.60	.06	.20	.20	.54
--	(798 NF)	(.40 NF)	.222	--	.06	--	--	--
110,000	3717	--	.111	.80	.08	.18	.22	.68
109,000	2335	.13	.362	--	.08	--	--	--
109,000	2637	.13	.222	.76	.08	.14	.22	.67
107,500	3409	.185	.128	.74	.10	.22	.32	.68
106,800	2923	.18	.162	.75	.05	.20	.30	.65
105,500	2950	.16	.236	.78	.12	.16	.26	.68
101,300	3058	--	.080	--	--	--	--	--
100,000	4342	.25	.194	.78	.08	.20	.30	.72
100,000	4298	.22	.236	.78	.16	.16	.25	.58
99,000	4175	.275	.177	.80	.24	.24	.32	.70
87,000	6495	.45	.081	.80	.14	.36	.48	.75
82,500	9842	.44	.097	.78	.25	.28	.38	.72
121,000	2830	--	--	--	.22	.22	.25	.35
116,500	3150	.21	.432	.94	.12	.12	.15	.90
111,000	3066	.21	.439	--	--	.10	--	--
111,000	3446	.21	.221	--	--	.30	--	--
91,500	7520	.59	.475	1.08	.25	.42	.55	.95
91,500	(5385 NF)	(.06 NF)	.007	--	--	--	--	--
91,500	10863	.51	.059	1.08	.20	.44	.65	1.00
91,500	6998	.54	--	--	--	--	--	--
91,500	6636	.52	--	--	--	--	--	--

fissuring

*Maximum stress description

**Disregarding point of failure, remaining cracks only

***Deepest crack

****Zone 5

B

TABLE III

Results of Hydraulic Fatigue Test and Examination After Testing of Cylinders from Tubes N, E, F, G, I and K

Cylinder Number	Wall Ratio (OD/ID)	Maximum Internal Pressure Prior to Hydraulic FatigueTest psi	.01% offset Yield Strength Pressure psi	Test Internal Pressure psi	**Equivalent Uniaxial Stress psi	Life cycles	Depth to Zone 4 to Point of Shear
N-10	1.2	25,000	21,500	20,000	118,000	4657	
N-9	1.2	22,000	21,000	20,000	111,000	4414	
N-5	1.57	57,000	51,250	52,000	122,200	2600	
N-8	1.57	59,000	54,750	49,000	115,000	3234	
*N-4	1.57	59,000	53,500	44,000	103,500	4707	
N-3	1.6	61,000	54,750	56,000	128,000	2927	
E-10	1.57	56,000	52,500	50,000	117,500	5285	
E-9	1.57	--	--	56,000	131,500	315	
E-8	1.57	--	--	50,000	117,500	3673	
*E-5	1.57	--	--	45,000	106,000	7240	
E-4	1.57	--	--	40,000	94,100	12285	
F-10	1.57	69,000	66,000	60,000	141,000	4162	
F-9	1.57	--	--	60,000	141,000	2542	
F-4	1.57	--	--	55,000	129,300	2858	
F-3	1.57	--	--	50,000	117,500	4850	
F-8	1.57	--	--	50,000	117,500	9726	
*F-5	1.57	--	--	45,000	106,000	11719	
G-10	1.57	84,000	75,500	60,000	141,000	3042	
G-9	1.57	--	--	60,000	141,000	2832	
G-8	1.57	--	--	50,000	117,500	9306	
*G-5	1.57	--	--	45,000	106,000	17791	
I-7	1.845	70,000	67,000	60,000	110,000	5932	
I-8	1.845	70,000	65,500	52,000	35,100	11374	
I-10	1.845	70,000	66,000	48,000	87,900	20411	
I-14	1.23	23,000	22,300	21,000	102,500	6734	
I-16	1.23	23,000	23,000	19,000	92,600	8321	
I-15	1.23	23,000	22,000	17,000	83,000	16250	
K-10	1.57	60,000	58,000	60,000	141,000	3670	.45
K-9	1.57	--	--	50,000	117,500	6341	.66
K-8	1.57	--	--	45,000	106,000	9575	.82
K-5	1.57	--	--	38,000	89,400	25102	.78

* = Only cylinders examined.

** = Maximum stress description.

*** = Disregarding point of failure, remaining cracks only.

FIGURES 1 to 13

PERCENT OFFSET ON THE OUTSIDE DIAMETER EQUIVALENT TO .01% OFFSET ON THE INSIDE DIAMETER AS A FUNCTION OF WALL RATIO

PERCENT OFFSET ON O.D. $= \frac{.02}{.7+1.3W^2}$

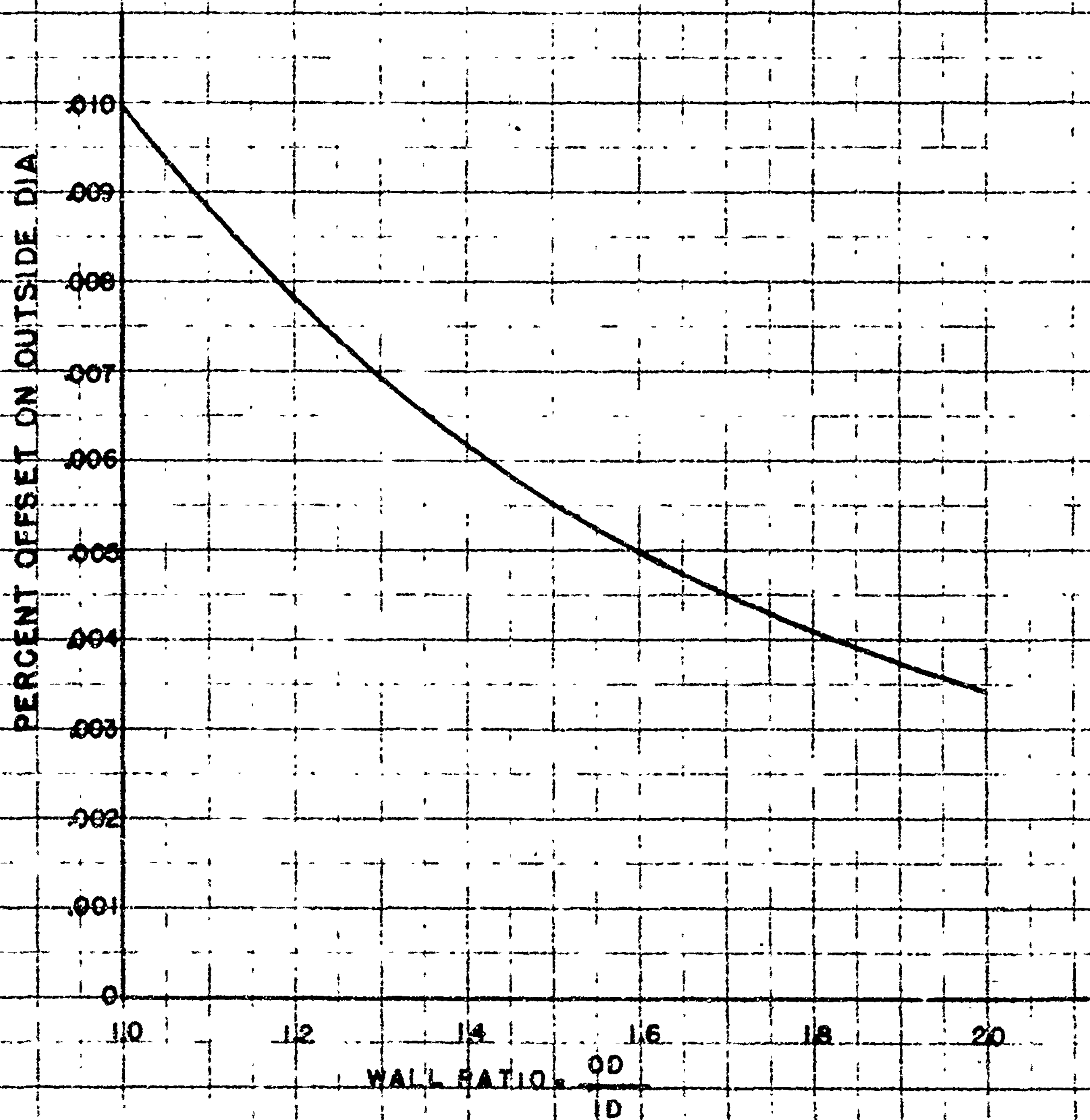
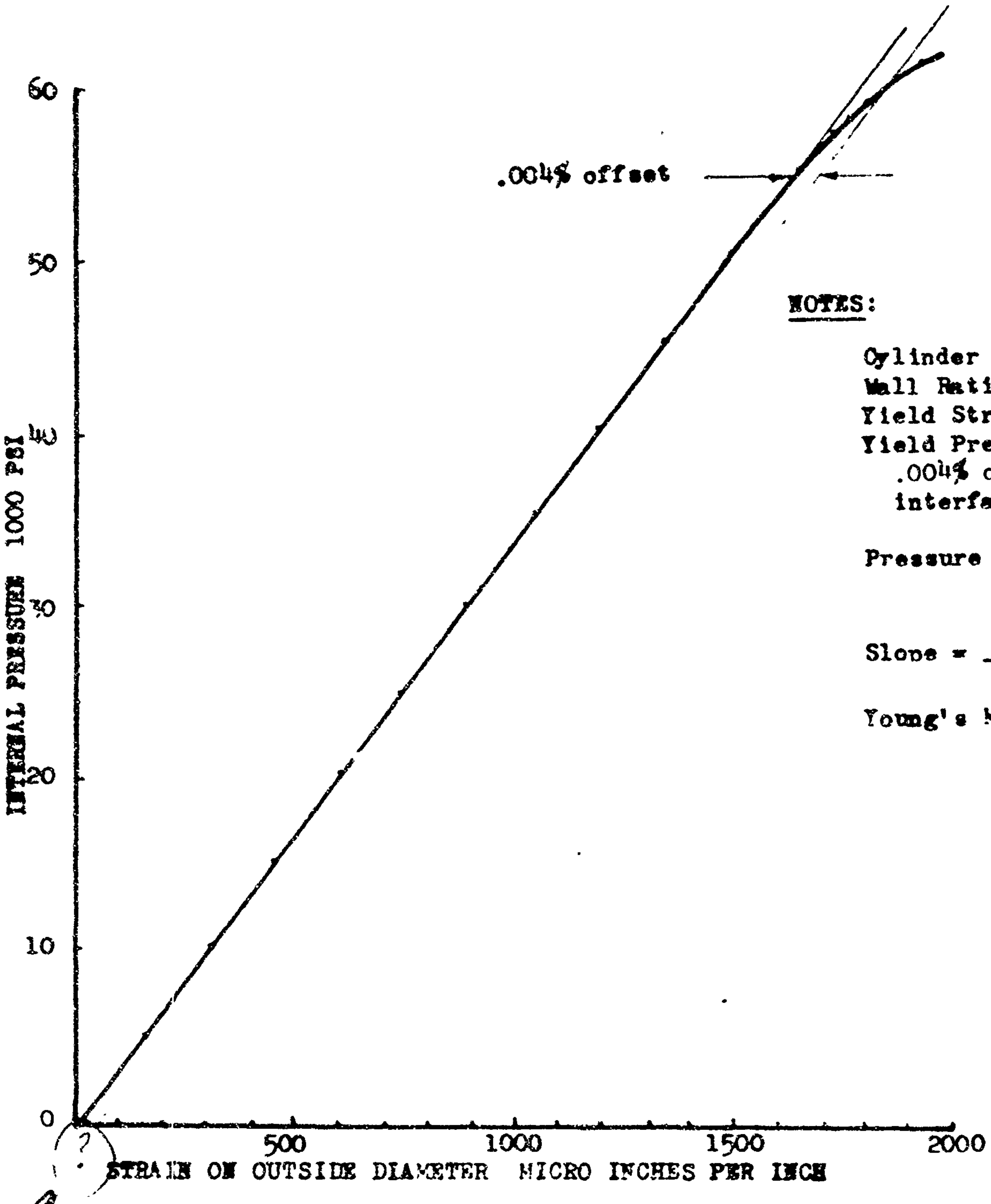


FIG.1



YIELD STRENGTH DETERMINATION OF A SECTION OF A COLDWORKED GUN TUBE

NOTES:

Cylinder D-2
Wall Ratio = 1.8
Yield Strength (0.01% offset) of Steel Before Coldwork = 85,880 psi
Yield Pressure (0.01% offset) of Section = 57,500 psi from Fig. I
.004% offset on outside is equivalent to 0.01% offset on bore interface.

$$\text{Pressure Factor} = \frac{\text{Yield Pressure (0.01\% offset) of section}}{\text{Yield Strength (0.01\% offset) of steel before coldwork}} = .675$$

$$\text{Slope} = \frac{\text{Internal Pressure}}{\text{Strain on Outside}} = 3.38 \times 10^7 \text{ psi}$$

$$\text{Young's Modulus } E = \frac{2 \times \text{slope}}{W^2 - 1} \text{ psi} = 30{,}100{,}000 \text{ psi}$$

Fig. 2

LOCI OF MAXIMUM AND MINIMUM PRESSURE AND STRAIN AT BEGINNING AND END OF EACH CYCLE DURING THE TEST OF CYLINDER D-12

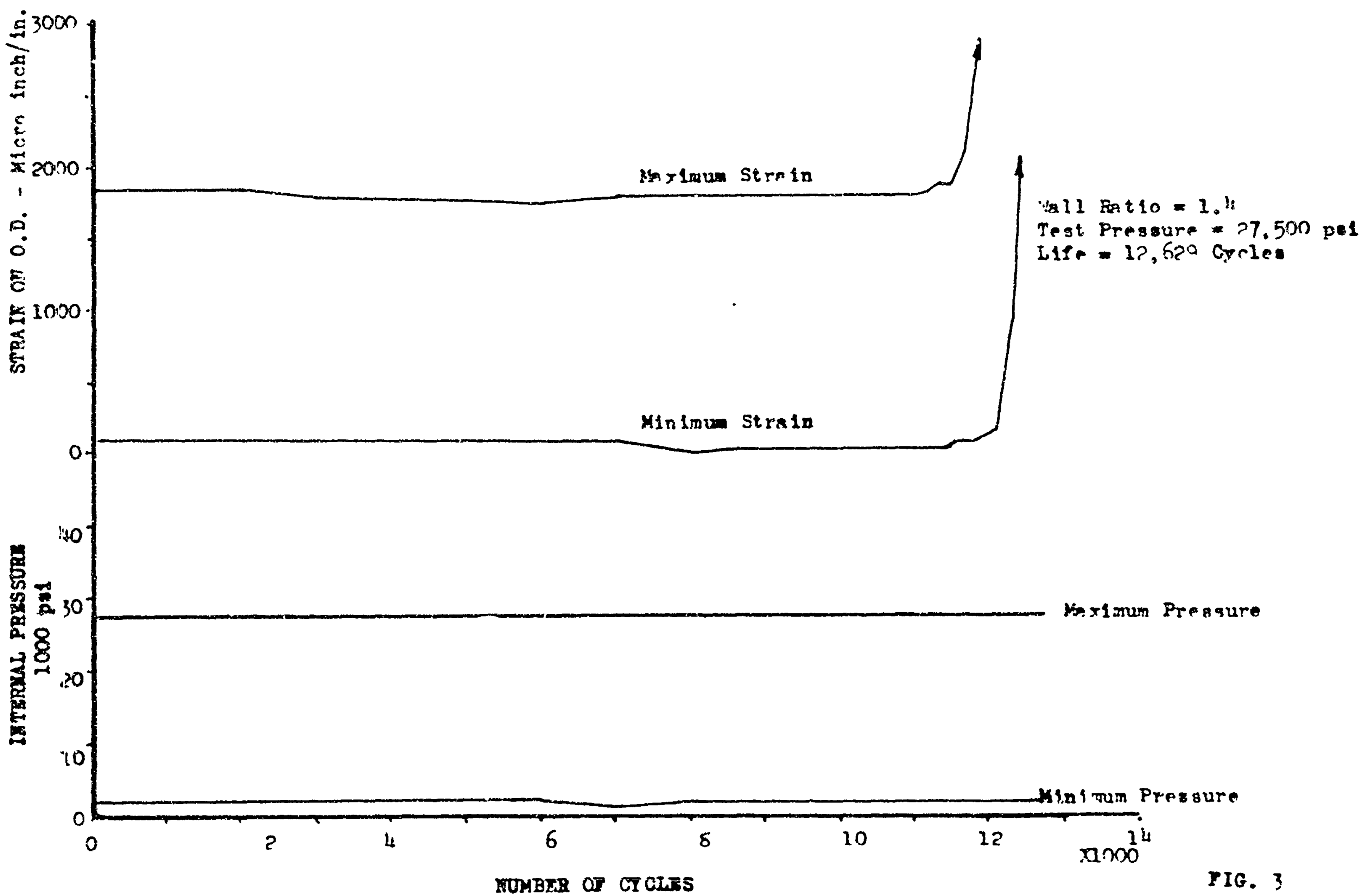
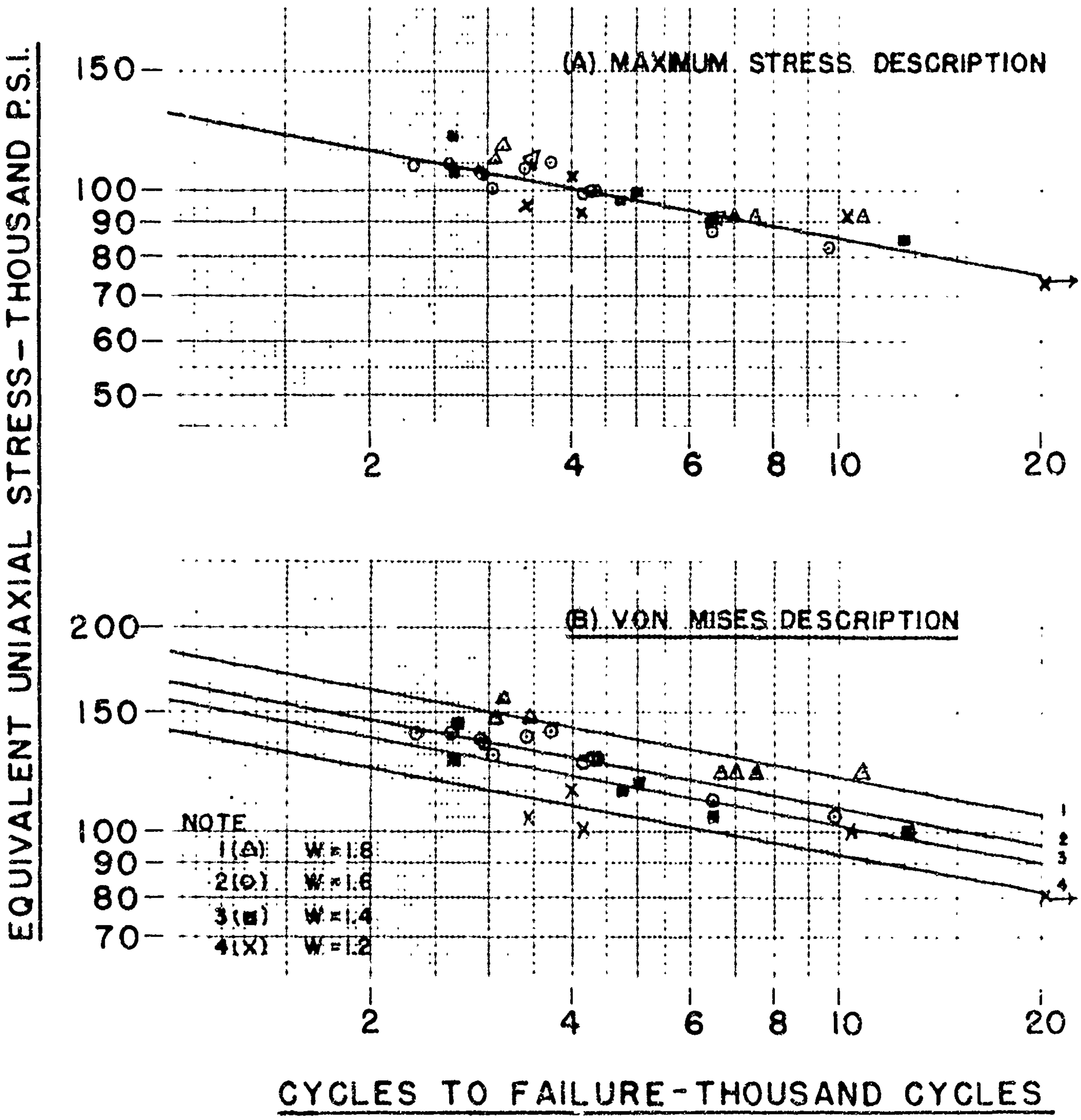


FIG. 3

HYDRAULIC FATIGUE TEST RESULTS - A,B,C,D TUBES

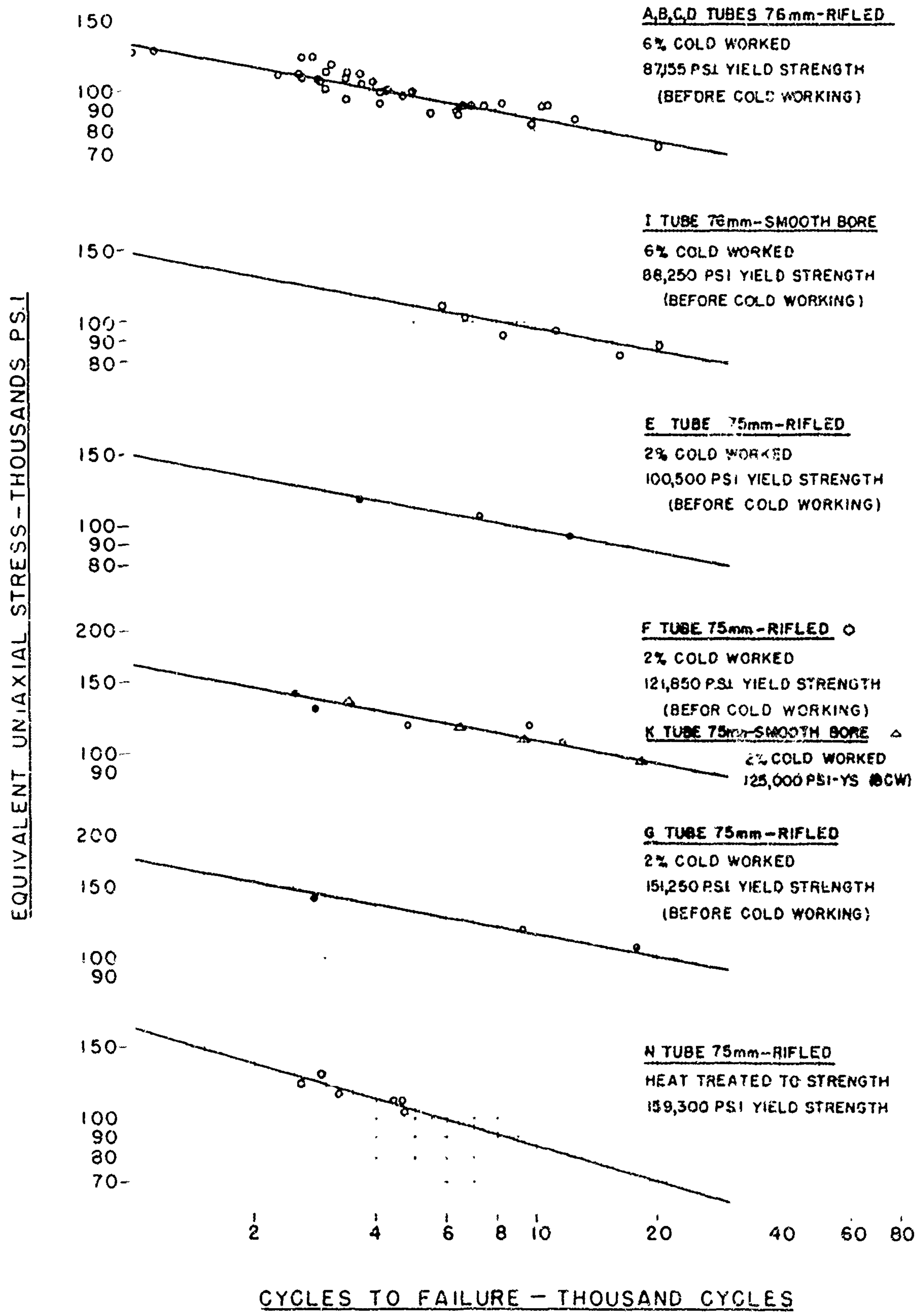
IN TERMS OF EQUIVALENT UNIAXIAL STRESS



WTN.639-8714

FIGUER 4

RELATIONSHIP BETWEEN EQUIVALENT UNIAXIAL STRESS (MAXIMUM STRESS DESCRIPTION) AND NUMBER OF CYCLES TO FAILURE IN HYDRAULIC FATIGUE TESTS



WTN.639-9442

FIG. 5

RELATIONSHIP BETWEEN INTERNAL PRESSURE AND CYCLES TO FAILURE AS INFLUENCED BY WALL RATIO AND RIFLING FOR A,B,C,D AND I TUBES

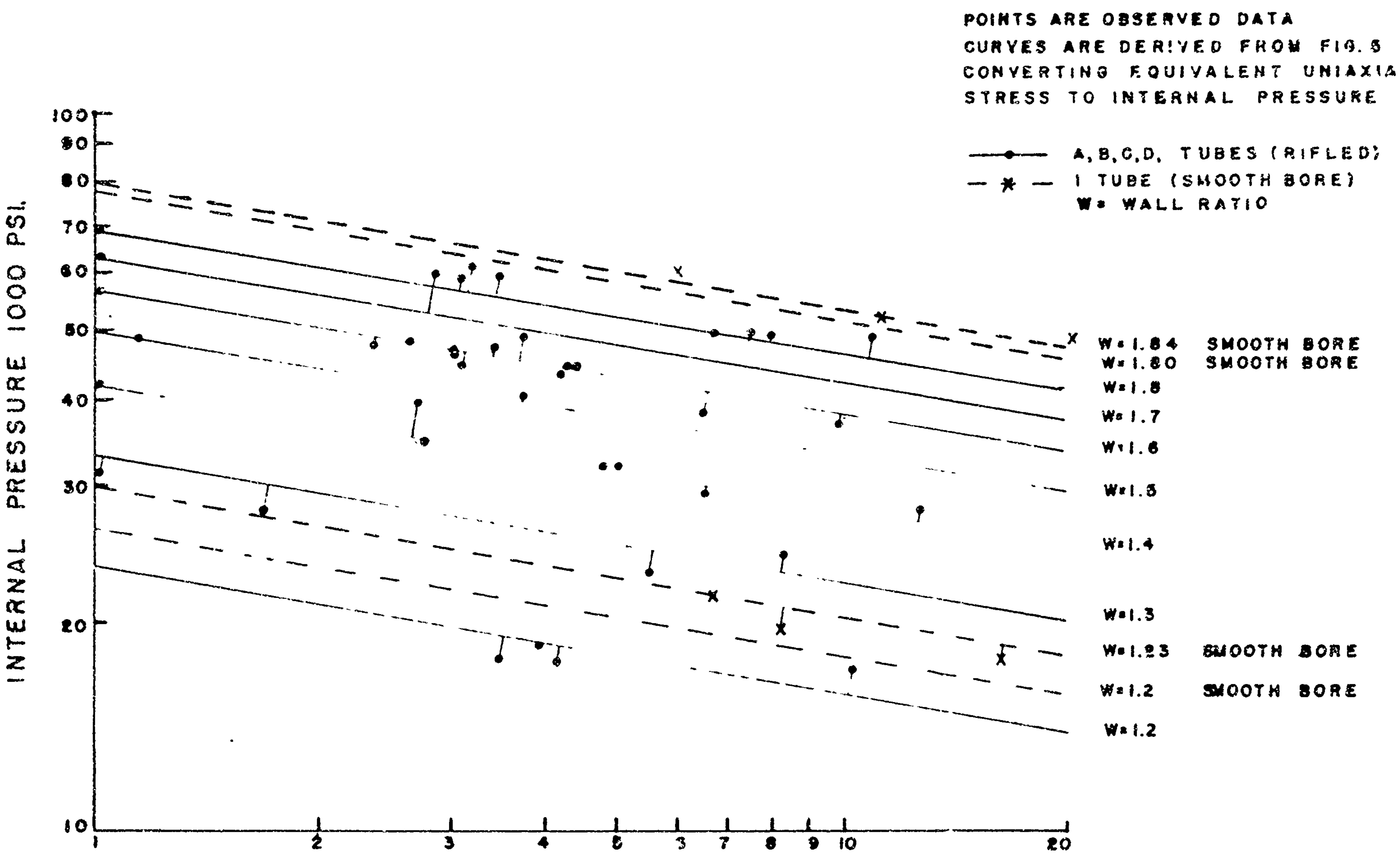


FIG. 6

RELATIONSHIP BETWEEN INTERNAL PRESSURE AND CYCLES TO FAILURE FOR E,F,G AND N TUBES

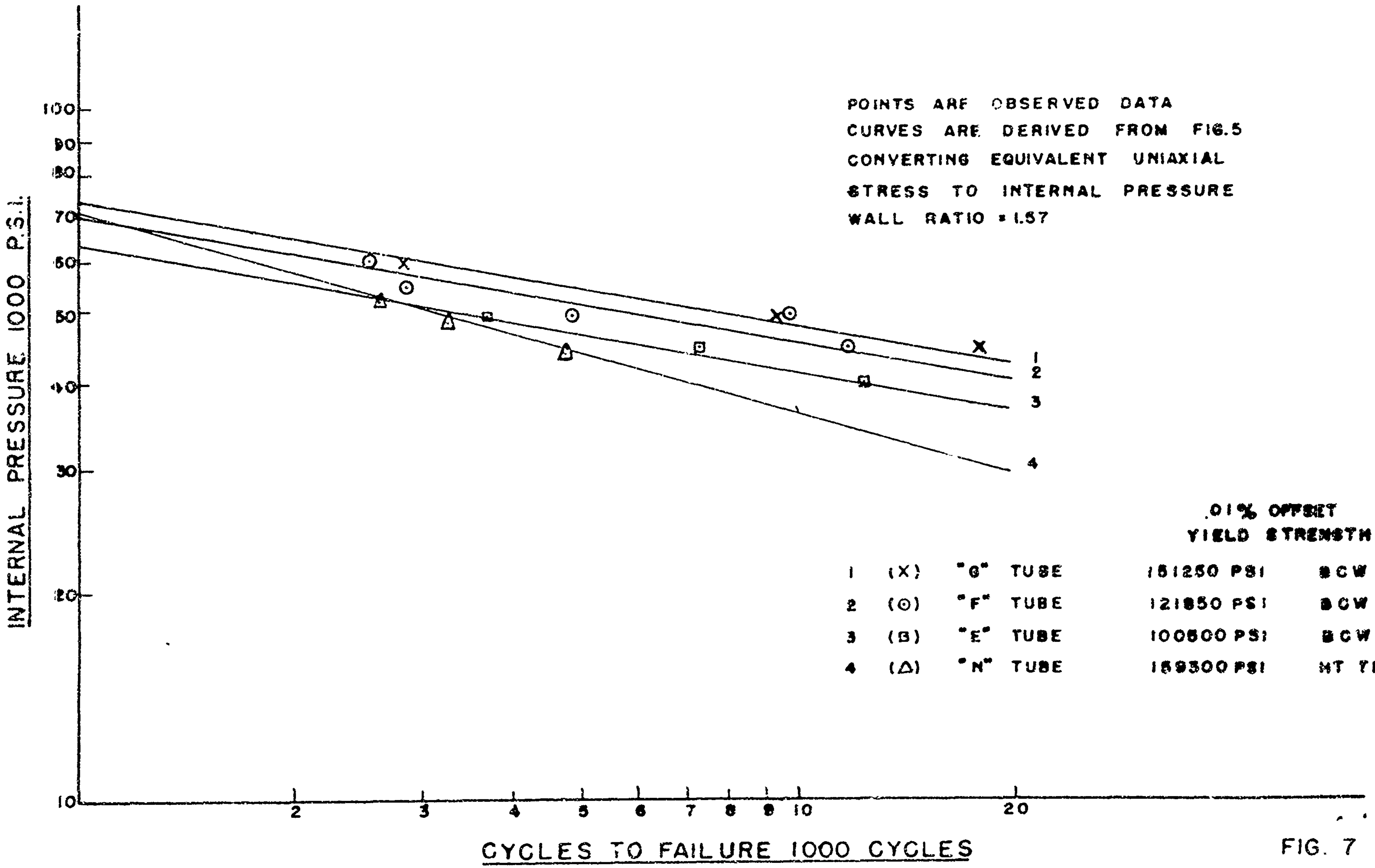
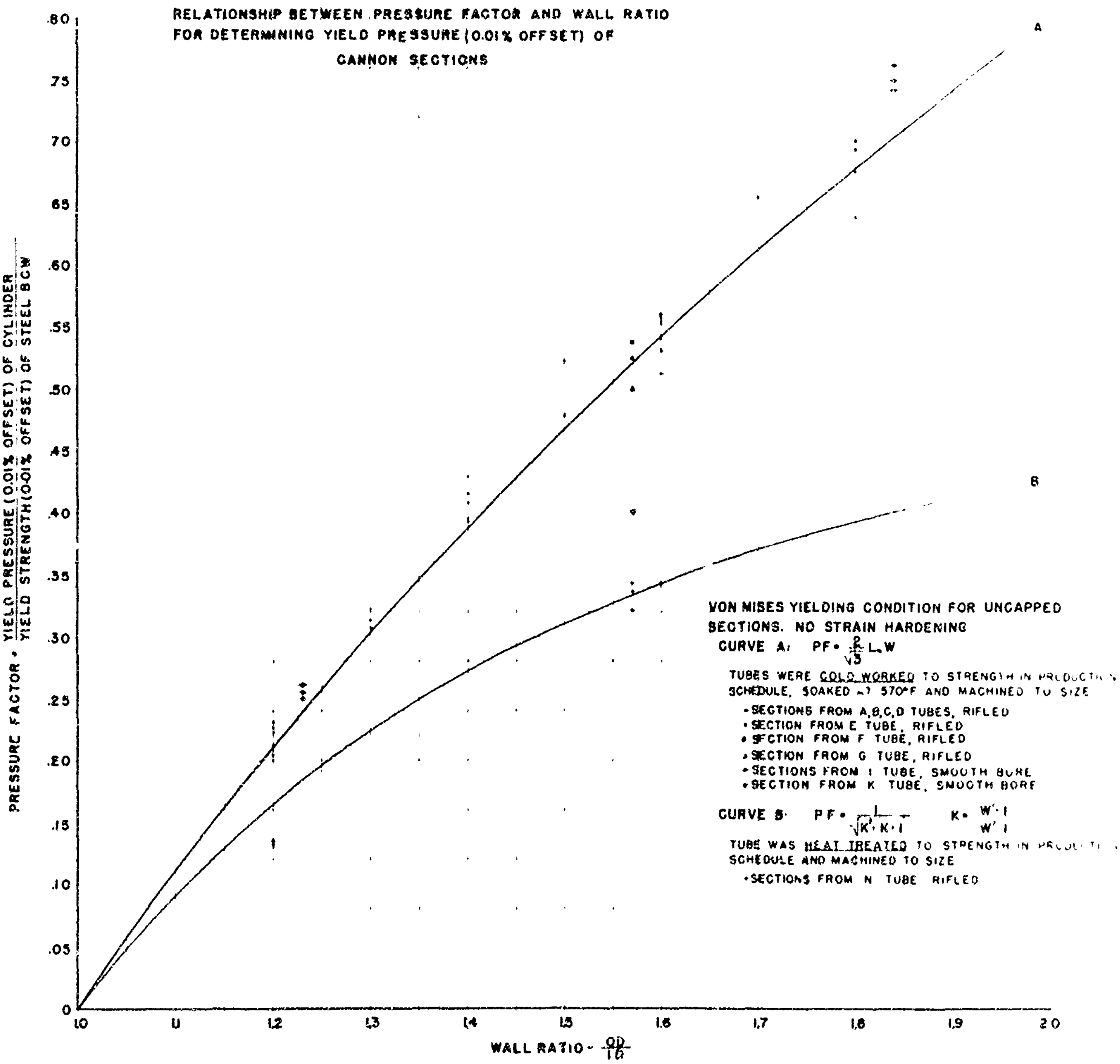
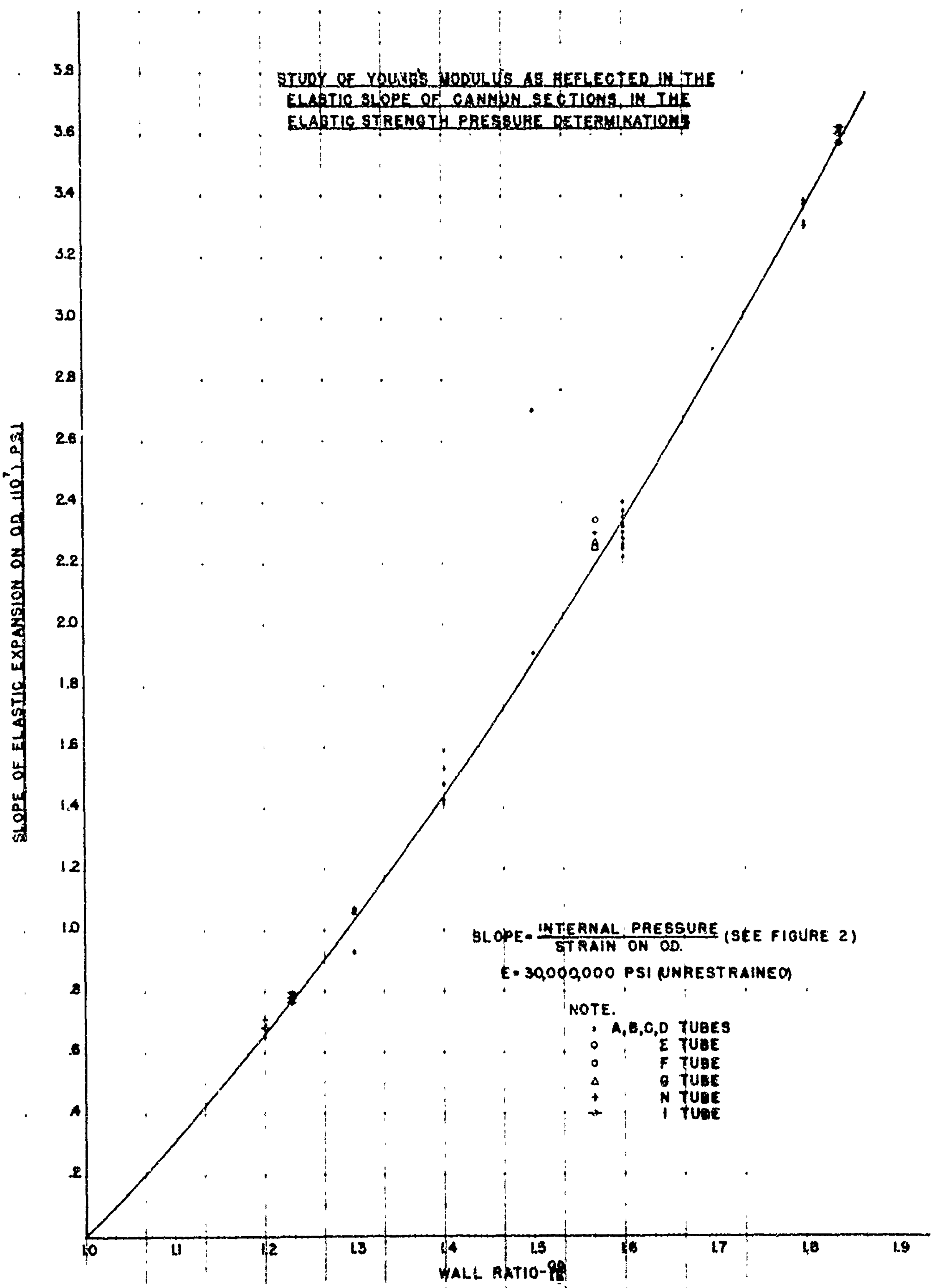


FIG. 7



WTN.639-0443

FIG. 8



WTN.639-8716

FIG. 9

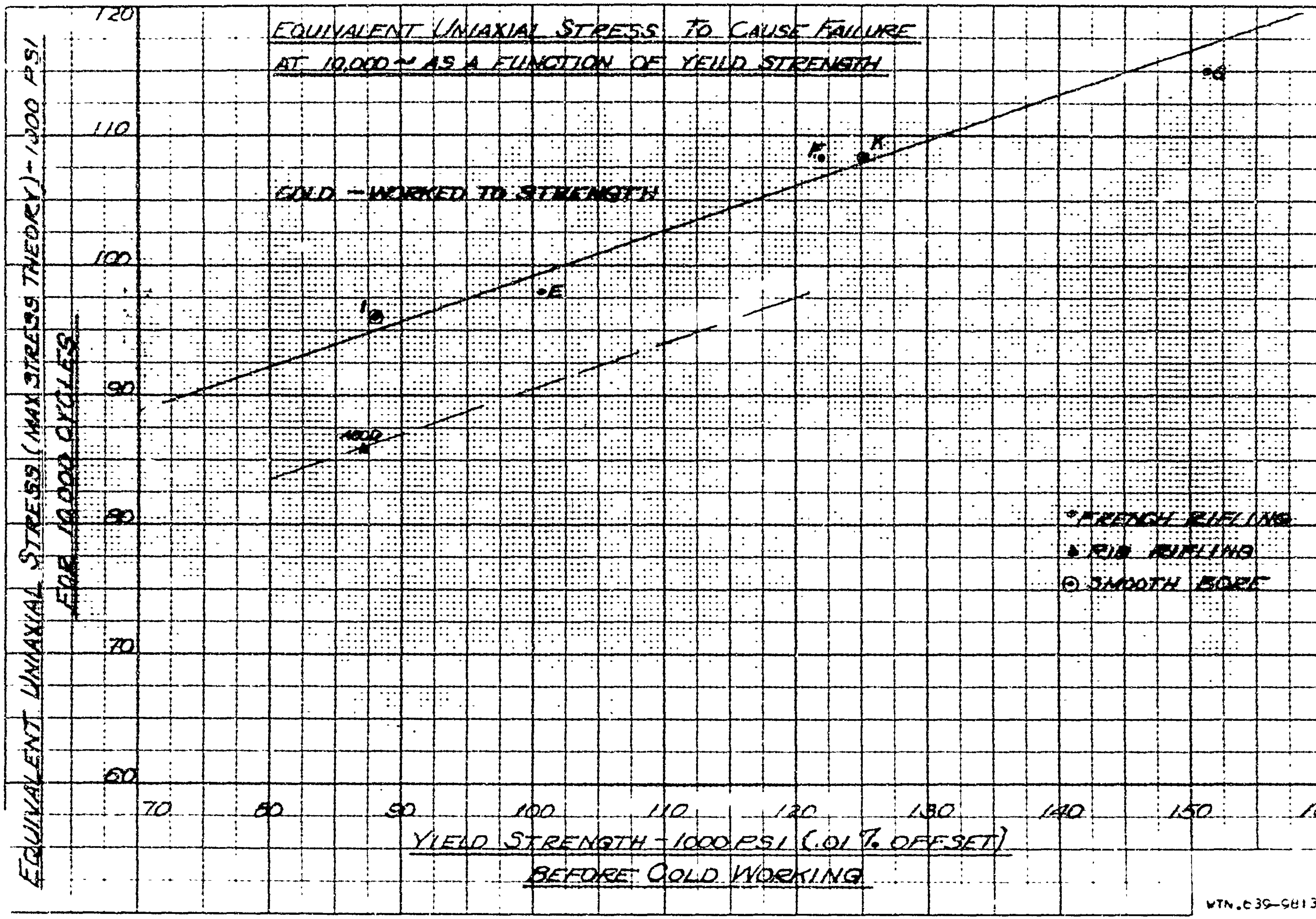

EQUIVALENT UNIAXIAL STRESS TO CAUSE FAILURE
AT 10,000 ~ AS A FUNCTION OF YEILD STRENGTH
COLD - WORKED TO STRENGTH
EQUIVALENT UNIAXIAL STRESS (MAX STRESS THEORY) - 1000 PSI
FOR 10,000 CYCLES
YIELD STRENGTH - 1000 PSI (.01 % OFFSET)
BEFORE COLD WORKING
FRENCH RIFLING
RIB RIFLING
SMOOTH BORE
120
110
100
90
80
70
60
70
80
90
100
110
120
130
140
150
E
K
WTN.639-9813

FIG. 10

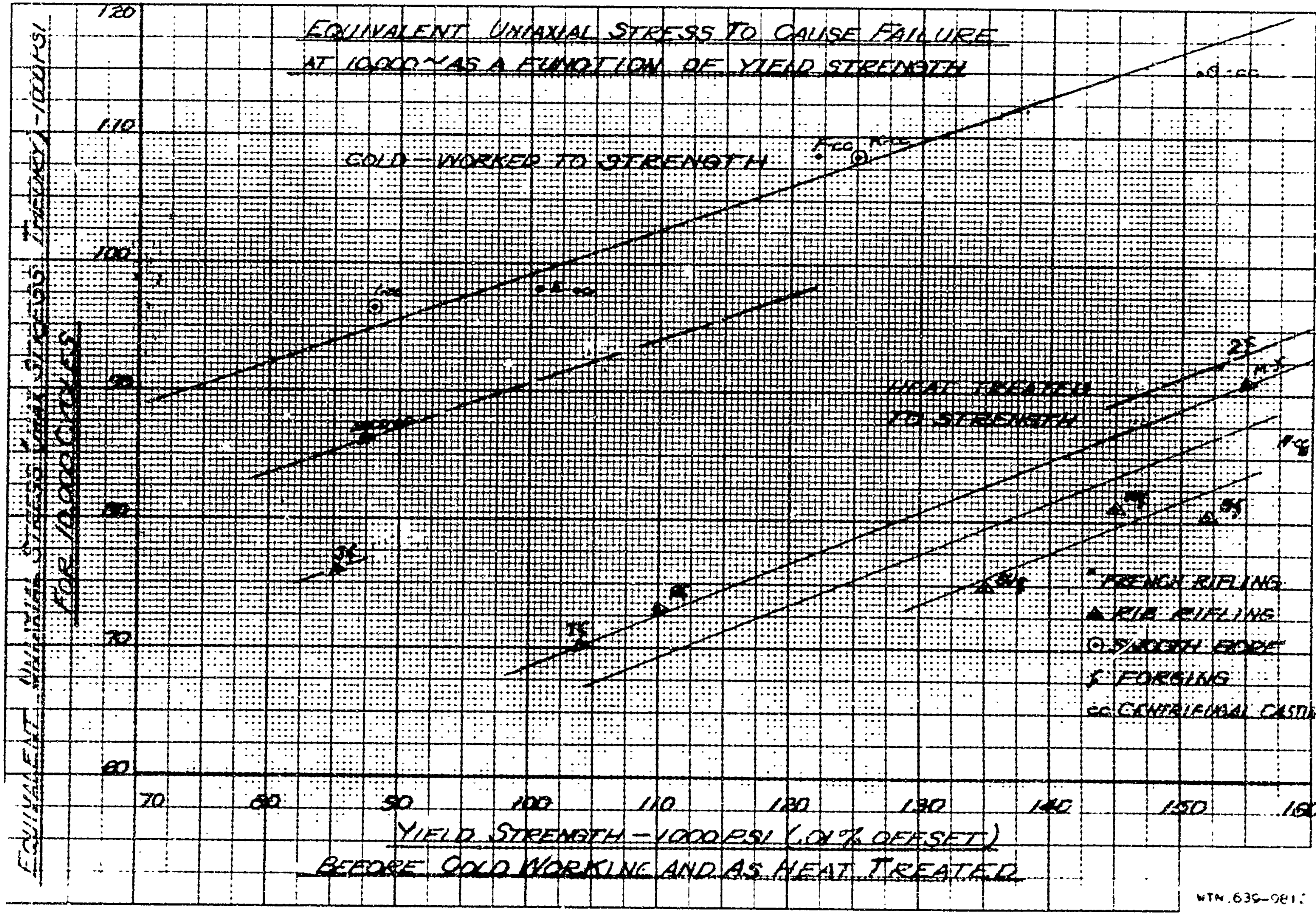
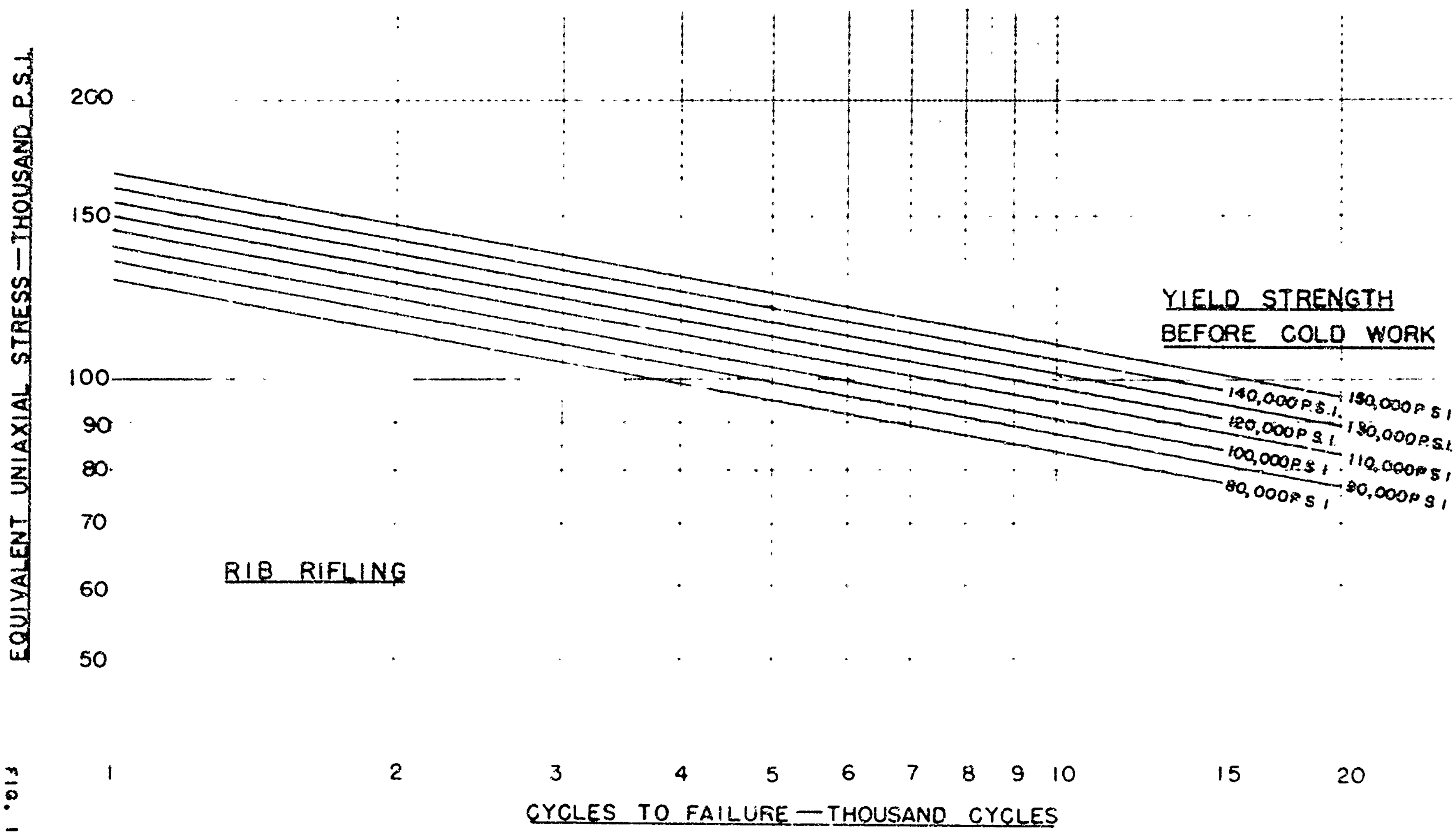


FIG. 11

WTN.639-0812

INFLUENCE OF YIELD STRENGTH BEFORE COLD WORKING (0.01% OFFSET) ON THE RELATIONSHIP OF EQUIVALENT UNIAXIAL STRESS (MAXIMUM STRESS DESCRIPTION) AND CYCLES TO FAILURE



WTN.639-9413

FIG. 12

INFLUENCE OF YIELD STRENGTH BEFORE COLD WORKING (0.01% OFFSET) ON THE RELATIONSHIP OF EQUIVALENT UNIAXIAL STRESS (MAXIMUM STRESS DESCRIPTION) AND CYCLES TO FAILURE

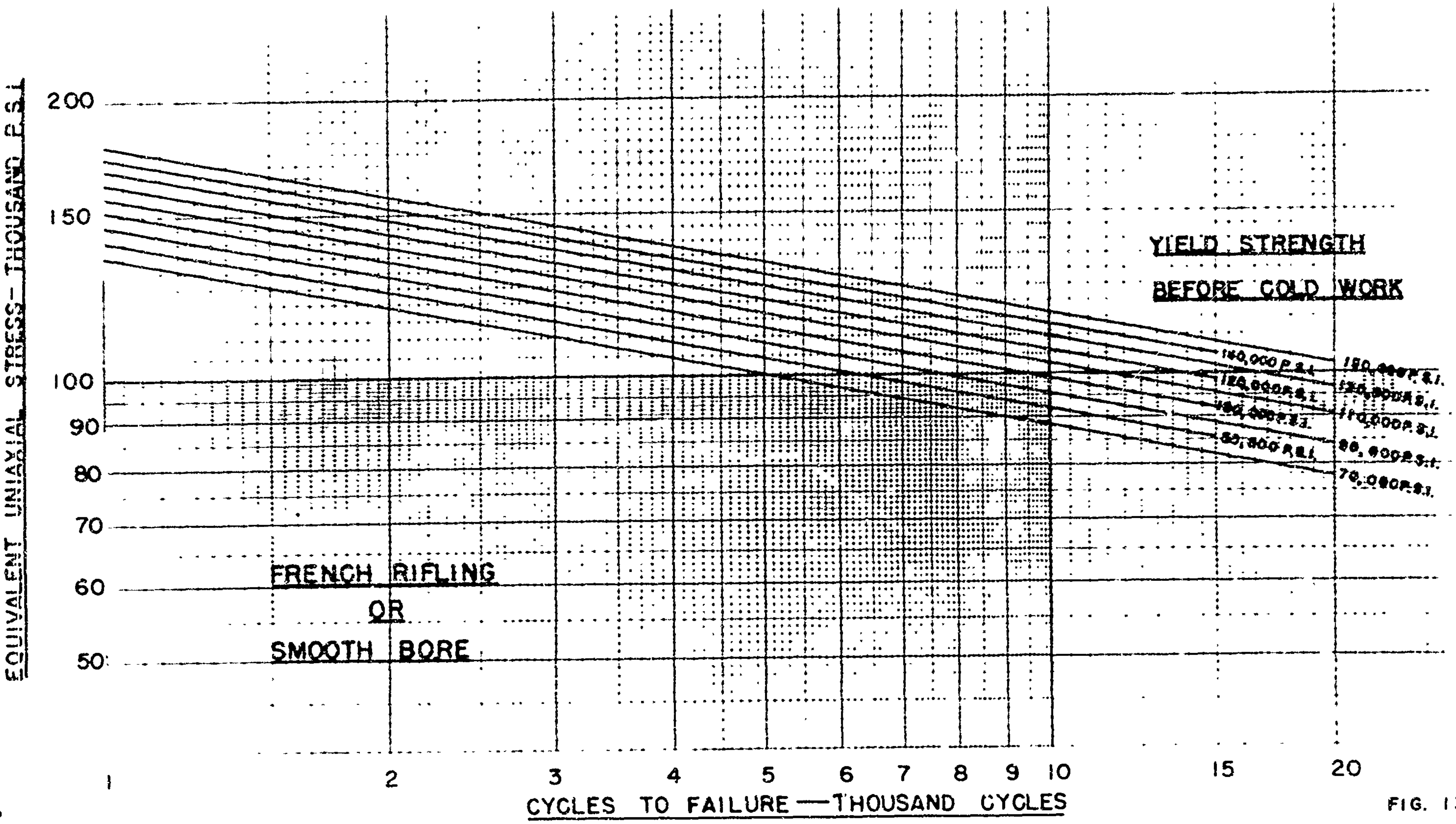


FIG. 13

WTN.639-9814

APPENDIX A

Description of Equipment, Controls and Specimens

APPENDIX A

Test Equipment

Description of Equipment, Controls and Specimens

The test equipment* initially used for these hydraulic fatigue studies has been considerably improved. It is comprised of apparatus to apply cyclic applications of pressure internally to sections of cannon tubes in order to produce mechanical deterioration of the specimen similar to that found in tubes returned from service. The equipment now in use to generate high pressure, to measure, release, recycle, and to count the cycles is shown schematically in Fig. 14. In Fig. 15 are photographs of the control panel, the pressure intensifier, a press with a specimen mounted in place and a solenoid operated control valve. The pressure intensifier, press and control valves are set in a pit, remote from the control room, while the low pressure pump is set up in still another room. This arrangement was made to reduce the hazard to the operators. Since the equipment and the specimen sometimes fragment on failure, the specimen is further isolated by armor plate bolted around the press.

As indicated to the right of Fig. 14 the hydraulic pressure is generated in two stages; an ordinary commercial pump constitutes the first, supplying pressure up to 6,000 psi, maximum, to the low side of the intensifier, which constitutes the second stage. The intensifier multiplies the pump pressure by the ratio of areas on the two sides of the high pressure piston. This ratio is 15. The maximum pressure is therefore 90,000 psi.

The high pressure side is a closed elastic system, the pressure in which is controlled by means of manganin coils, which through relays, operate the valve on the low pressure side of the intensifier. The pump runs continuously drawing water from the reservoir. When the solenoid valve is open, the water is pumped back to the reservoir and the water is drained from the intensifier to the reservoir. When the valve is closed the water is pumped into the low pressure side of the intensifier. The manganin coils, when subjected to hydrostatic pressure change in resistance in direct proportion to the pressure. One coil is used in conjunction with a special direct current wheatstone resistance bridge to measure slowly applied pressure. The accuracy is well within 100 psi. This setup makes it possible to set accurately the high pressure "knock off" relay in the pressure indicator and controller. Two other manganin coils are used, one in conjunction with the pressure indicator and controller and the other with the pressure recorder and controller. These instruments are basically of the same type**. They are AC bridges kept in null balance at all times by electronics. The relays in both instruments are of the brush contact type and are actuated in the indicator

---

*Watertown Arsenal Laboratory Report No. 731/158: "Hydraulic Fatigue Tests of Rifled Cannon Sections" By: Capt. D. H. Newhall

**Developed by the Foxboro Co., Foxboro, Mass.

with the displacement of the indicating needle, and in the recorder with the displacement of the recording pen. In both instruments ample range in adjustment of the point of high pressure release is provided. However, the pressure indicator is capable of more accurate pressure adjustment than the recorder and normally during the fatigue test releases the high pressure by actuating the solenoid operated valve to the reservoir on the low pressure side. The high pressure "knock off" on the pressure recorder has a relatively coarser adjustment because of the shorter scale length and, as used, is set at a pressure level very slightly higher than that on the indicator. In case the indicator fails, the recorder would take over its "knock off" function and prevent an over-shot in pressure. As the high pressure falls after "knock off" and approaches zero pressure (somewhere under 1,000 psi) the Retax on the pressure recorder closes the solenoid operated valve starting a new cycle.

The electrical circuits are arranged so that a failure of power in the measuring system will open the low pressure valve and thus protect the test specimen. The cycles are counted by a magnetic counter which is energized each time the low pressure valve solenoid functions.

Fig. 14 is a drawing showing the typical gun layout and the specimen used in the study of a medium caliber tube. After the cylinders were cut from the gun tubes the rifling was removed from each end region in order to provide space for the packings. Then the outside diameter was machined to the desired value, care being taken to make the outside concentric with the inside. The length of the 75mm. and 76mm. test sections was 12.5". The diameters for the various wall ratios and the wall thicknesses based on the groove diameter were as shown in the following tabulation:

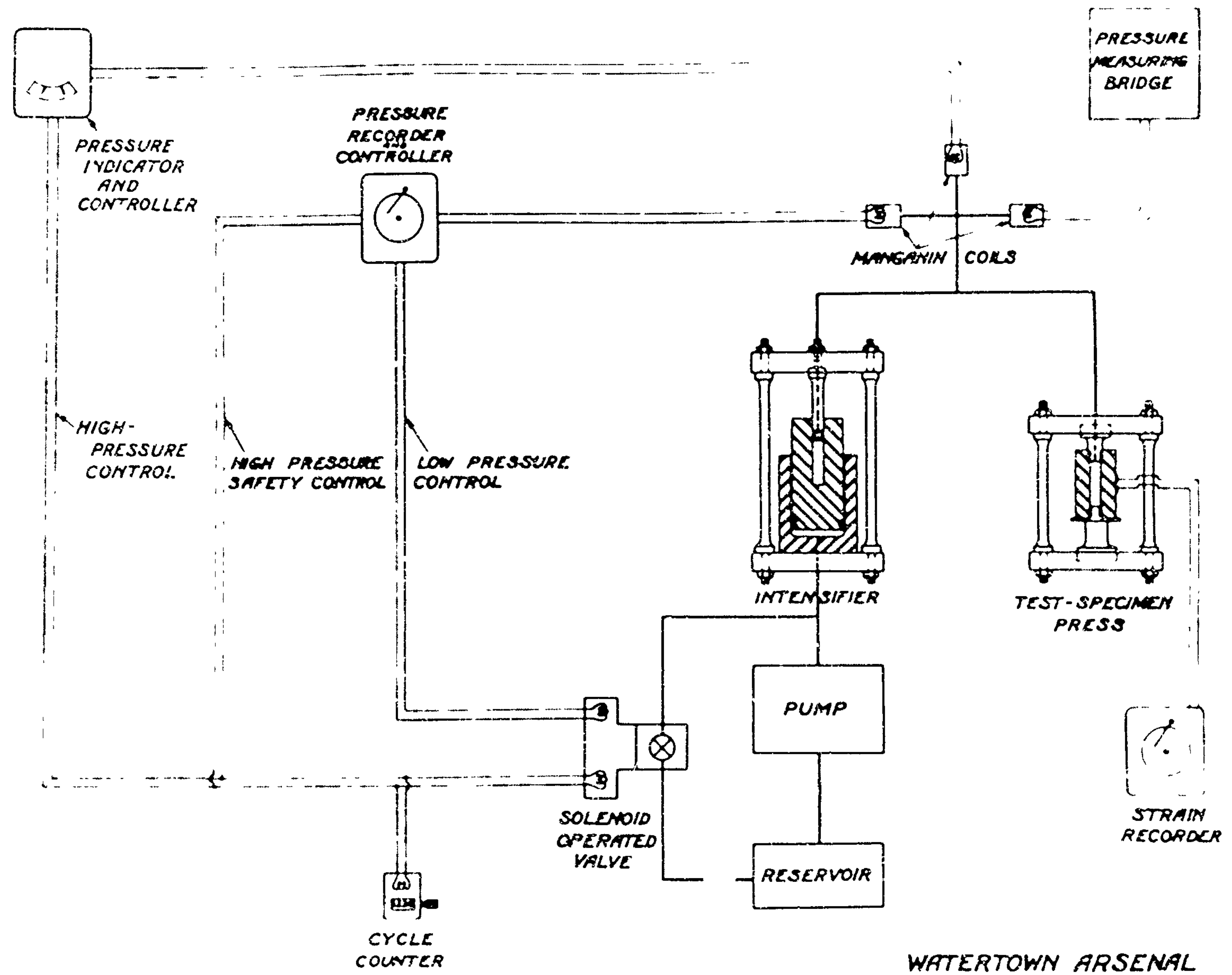
TABLE IV

Wall Ratio	Diameter, inches: 75mm. Caliber, Inside, Lands	75mm. Inside, Grooves	75mm. Outside	76mm. Caliber, Inside, Lands	76mm. Inside, Grooves	76mm. Outside	Wall Thickness, in. 75mm.	Wall Thickness, in. 76mm.
1.2	2.950	2.990	3.588	3.000	3.080	3.696	.299	.308
1.232*				3.000	3.000	3.696		.348
1.3				3.000	3.080	4.004		.462
1.4	2.950	2.990	4.186	3.000	3.080	4.312	.598	.616
1.5				3.000	3.080	4.620		.770
1.572	2.950	2.990	4.700				.855	
1.57*	2.950	2.950	4.632				.841	
1.6	2.950	2.990	4.784	3.000	3.080	4.928	.897	.924
1.7				3.000	3.080	5.236		1.078
1.8				3.000	3.080	5.544		1.232
1.848*				3.000	3.000	5.544		1.272

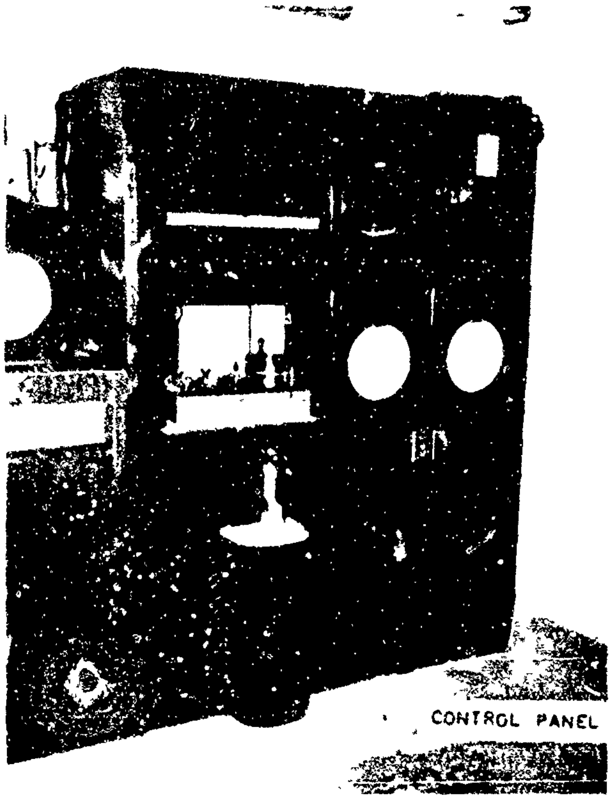
*Smooth Bore

It was found necessary to measure and record the strain on the outside of the test specimen on each cycle in order to be sure that full pressure always reached it. The pressure line can become plugged in such a manner that the cylinder does not receive full pressure while the controller does. SR4 strain gages are applied transversely to the outside of the cylinder at midlength. Baldwin-Southwark SR4 strain measuring and recording equipment made by the Foxboro Company is used. This is indicated on the lower right of Fig. 14.

SCHEMATIC SKETCH OF HYDRAULIC FATIGUE TEST EQUIPMENT

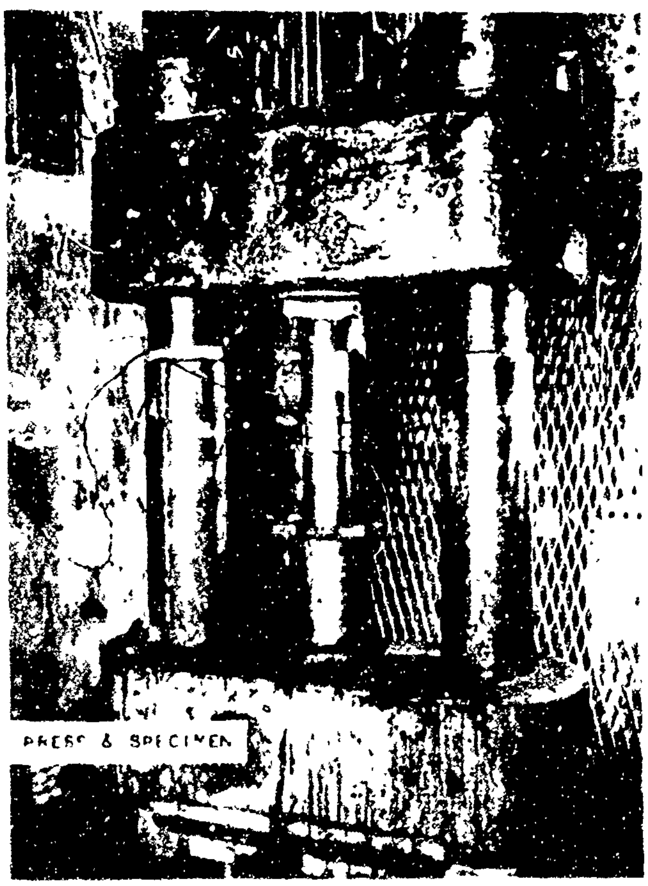


WATERTOWN ARSENAL
MAR 2 1945

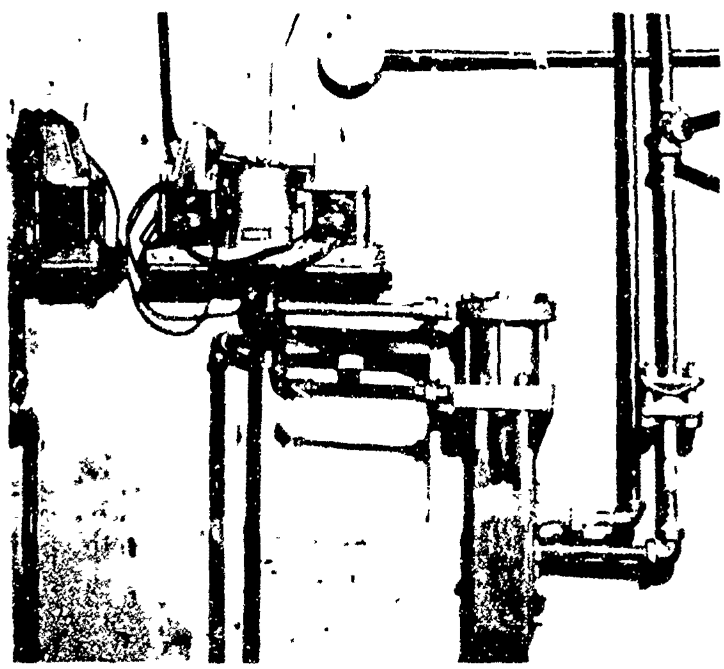


CONTROL PANEL

INTENSIFIER



PRESS & SPECIMEN



SOLENOID OPERATED CONTROL VALVE

WATERTOWN ARSENAL

EQUIPMENT USED TO GENERATE, CONTROL AND RE-CYCLE HIGH PRESSURE FOR HYDRAULIC FATIGUE TESTING. 2? JUNE 1948 WTN.60-?.16

FIG. 15

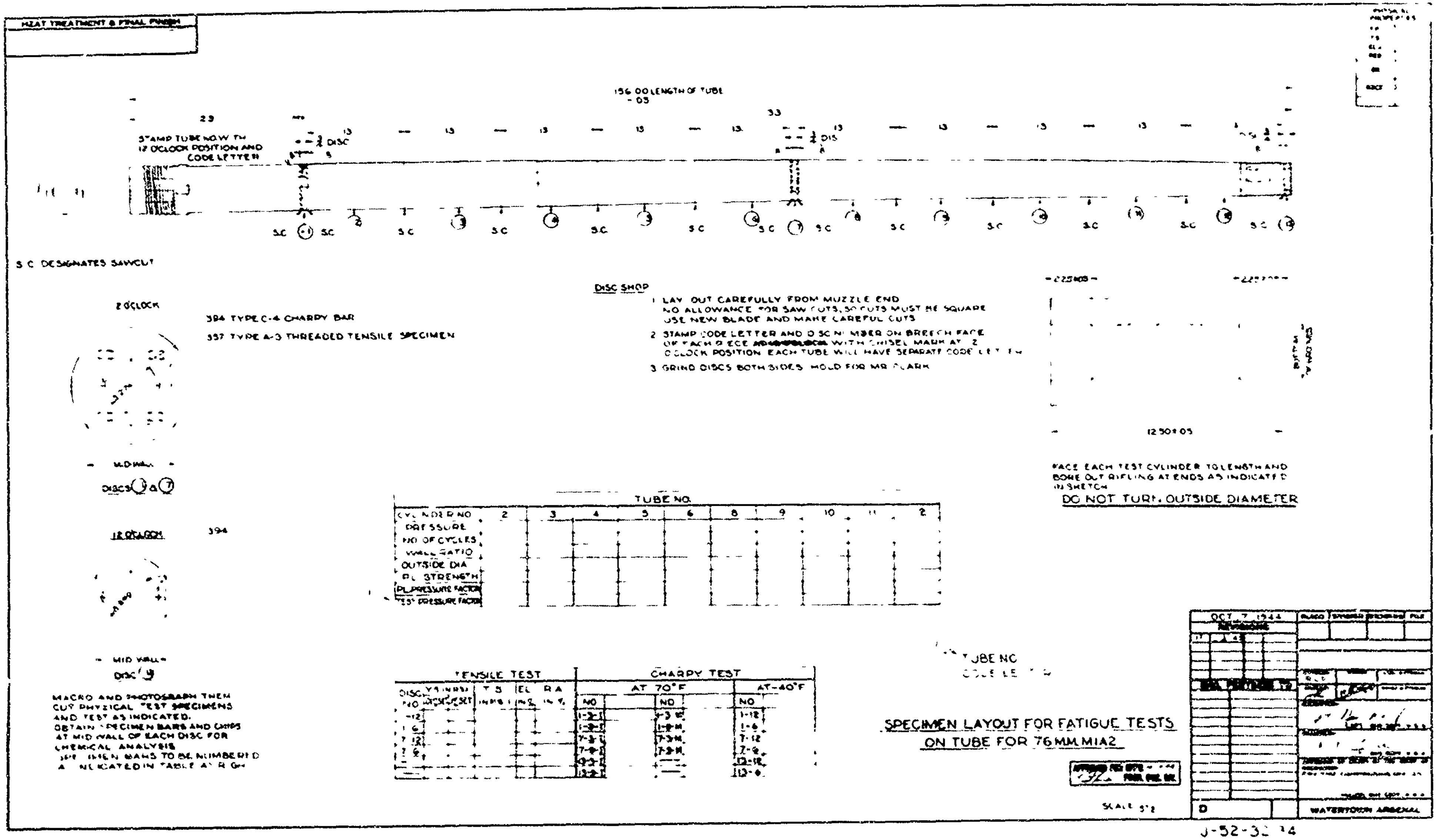


FIG. 16

WTN.639-8744

APPENDIX B

DATA SHEETS GIVING PERTINENT METALLURGICAL HISTORY OF STEEL FOR TUBES A, B, C, D, E, F, G, I, K, and N

DATA SHEET NO. 1

PERTINENT METALLURGICAL HISTORY OF STEEL

CALIBER AND MODEL: 76mm. M1A2 SERIAL NUMBER: 3J-2524 - A Tube

STEEL PRODUCER: Watertown Arsenal HEAT NUMBER: 3J-2524

STEEL FABRICATOR: Watertown Arsenal METHOD OF FABRICATION: Cent. Casting
Normalized at 2200°F
Annealed at 1600°F

MACHINING CONTRACTOR: Cowdrey Machine Works

FINAL HEAT TREATMENT: (DIMENSIONS OF CROSS SECTION I.D.=2.0" O.D.=8-1/4 to 5½")

QUENCH TEMP., °F 1650 TIME OF HOLD, HRS. 6 MEDIUM W.Q.

DRAW TEMP., °F 1255 TIME OF HOLD, HRS. 6 MEDIUM F.C.

STRESS RELIEF TEMP., °F ______ TIME OF HOLD, HRS. ______ MEDIUM ______

COLD WORK, %: 6 nominal; 8.9 max; 4.3 min; 6.0 ave.
SOAK TEMP. °F 570 6 F.C.

CHEMICAL COMPOSITION %:

C	Mn	Si	Ni	Cr	Mo	V
.28	.63	.30	--	.98	.52	.08

AVERAGE TRANSVERSE MECHANICAL PROPERTIES:

		Yield Strength, PSI .01% Set	Yield Strength, PSI .1% Set	Tensile Strength PSI	Red. Area %	Charpy* Ft. Lb.
Before Coldwork:	Breech	88,750	--	109,200	62.3	--
	Muzzle	88,250	--	107,750	62.0	--
After Coldwork:	Breech	102,500	--	114,650	62.0	16.8-23.7 at 70°F
	Midlength	103,250	--	122,250	54.0	18.4-44.1 at 70°F
	Muzzle	--	--	--		16.4-20.1 at 70°F
					(Breech)	6.6-16.8 at -40°F
					(Midlength)	11.4-15.8 at -40°F
					(Muzzle)	14.8-15.5 at -40°F

*Range in values is reported.

W.Q. = Water Quench
F.C. = Furnace Cool

DATA SHEET NO. 1

PERTINENT METALLURGICAL HISTORY OF STEEL

CALIBER AND MODEL: 76mm. M1A2 SERIAL NUMBER: 40-268 - B Tube

STEEL PRODUCER: Watertown Arsenal HEAT NUMBER: 40-268

STEEL FABRICATOR: Watertown Arsenal METHOD OF FABRICATION: Cent. Casting Annealed at 1650°F

MACHINING CONTRACTOR: Cowdrey Machine Works

FINAL HEAT TREATMENT: (DIMENSIONS OF CROSS SECTION I.D.=2.0" O.D. 5-1/4 to 5½")

QUENCH TEMP., °F 1650 TIME OF HOLD, HRS. 6 MEDIUM W. Q.

DRAW TEMP., °F 1270 TIME OF HOLD, HRS. 6 MEDIUM F. C.

STRESS RELIEF TEMP., °F ______ TIME OF HOLD, HRS. ______ MEDIUM ______

COLD WORK, %: 6 nominal; 6.7 max; 4.9 min; 6.0 ave.
SOAK TEMP. °F 570 5½ F.C.

CHEMICAL
COMPOSITION %:

C	Mn	Si	Ni	Cr	Mo	V
.27	.79	.28	--	1.00	.51	.08

AVERAGE TRANSVERSE MECHANICAL PROPERTIES:

		YIELD STRENGTH, PSI .01% SET	YIELD STRENGTH, PSI .1% SET	TENSILE STRENGTH PSI	RED. AREA %	CHARPY* FT. LB.
Before Coldwork:	Breech	87,250	--	111,900	56.	--
	Muzzle	91,250	--	112,300	54.8	--
After Coldwork:	Breech	96,000	--	112,500	57.3	33-69 at 70°F
	Midlength	99,000	--	114,550	67.0	37½-66½ at 70°F
	Muzzle	--	--	--	--	24.7-39.5 at 70°F
					(Breech)	18½-20 at -40°F
					(Midlength)	20-25 at -40°F
					(Muzzle)	19.1-19.4 at -40°F

*Range in values is reported.
W.Q. = Water Quench
F.C. = Furnace Cool

DATA SHEET NO. 1

PERTINENT METALLURGICAL HISTORY OF STEEL

CALIBER AND MODEL: 76mm. M1A2 SERIAL NUMBER: 40-150 - C Tube

STEEL PRODUCER: Watertown Arsenal HEAT NUMBER: 40-150

STEEL FABRICATOR: Watertown Arsenal METHOD OF FABRICATION: Cent. Casting Annealed at 1650°F

MACHINING CONTRACTOR: Cowdrey Machine Works

FINAL HEAT TREATMENT: (DIMENSIONS OF CROSS SECTION ID=2.0" OD=5-1/4 to 5½")

QUENCH TEMP., °F 1650 TIME OF HOLD, HRS. 6 MEDIUM W.Q.

DRAW TEMP., °F 1280 TIME OF HOLD, HRS. 6 MEDIUM F.C.

STRESS RELIEF TEMP., °F ______ TIME OF HOLD, HRS. ______ MEDIUM ______

COLD WORK, %: 6 nominal 6.5 max: 4.6 min: 5.7 ave.
SOAK TEMP. °F 570 5½ F.C.

CHEMICAL COMPOSITION %:

C	Mn	Si	Ni	Cr	Mo	V
.29	.74	.26	--	1.03	.53	.10

AVERAGE TRANSVERSE MECHANICAL PROPERTIES:

		Yield Strength, PSI .01% Set	Yield Strength, PSI .1% Set	Tensile Strength PSI	Red. Area %	Charpy * Ft. Lb.
Before Coldwork:	Breech	83,500	--	107,200	58.7	--
	Muzzle	86,500	--	109,300	64.8	--
After Coldwork:	Breech	100,000	--	116,750	55.5	41-75 at 70°F 12½-19½ at -40°F
	Midlength	94,500	--	110,650	54.7	--

*Range in values is reported.
W.Q. = Water Quench
F.C. = Furnace Cool

DATA SHEET NO. 1

PERTINENT METALLURGICAL HISTORY OF STEEL

CALIBER AND MODEL: 76mm. M1A2 SERIAL NUMBER: 3J-2812 - D Tube

STEEL PRODUCER: Watertown Arsenal HEAT NUMBER: 3J-2812

STEEL FABRICATOR: Watertown Arsenal METHOD OF FABRICATION: Cent. Casting Annealed at 1650°F.

MACHINING CONTRACTOR: Cowdrey Machine Works

FINAL HEAT TREATMENT: (DIMENSIONS OF CROSS SECTION I.D.=2.0" O.D.= 8-1/4 - 5½")

QUENCH TEMP., °F	1650	TIME OF HOLD, HRS.	6	MEDIUM	W.Q.
DRAW TEMP., °F	1280	TIME OF HOLD, HRS.	6	MEDIUM	F.C.
STRESS RELIEF TEMP., °F		TIME OF HOLD, HRS.		MEDIUM	

COLD WORK, %: 6 nominal; 5.9 max; 4.6 min; 5.2 Ave.

SOAK TEMP. °F 570 5½ A.C.

CHEMICAL COMPOSITION %:

C	Mn	Si	Ni	Cr	Mo	V
.27	.80	.22	--	.97	.52	.095

AVERAGE TRANSVERSE MECHANICAL PROPERTIES:

		Yield Strength, PSI .01% Set	Yield Strength, PSI .1% Set	Tensile Strength PSI	Red. Area %	Charpy* Ft. Lb.
Before Coldwork:	Breech	4,500	--	107,000	61.6	
	Muzzle	250	--	108,900	59.4	
After Coldwork:	Breech	90,500	101,250	109,900	62.3	40-40 at 70°F inside 43-63 at 70°F midwall
	Midlength	99,000	105,500	113,600	63.2	31[illegible]-70 at 70°F inside 48[illegible]-66 at 70°F midwall
	Muzzle	--	--	--	--	63-66 at 70°F inside
						(Breech) 19-21 at -40°F inside (Midlength) [illegible] at -40°F inside (Muzzle) 2[illegible]-39 at -40°F inside

*Range in values is reported.

W.Q. = Water Quench

F.C. = Furnace Cool

A.C. = Air Cool

DATA SHEET NO. 1

PERTINENT METALLURGICAL HISTORY OF STEEL

CALIBER AND MODEL: 75mm, M5A1 SERIAL NUMBER: 4G-185 - E Tube

STEEL PRODUCER: Watertown Arsenal HEAT NUMBER: 4G-185

STEEL FABRICATOR: Watertown Arsenal METHOD OF FABRICATION: Cent. Casting
Annealed at 1700°F

MACHINING CONTRACTOR: Oldsmobile Div., G.M.C.

FINAL HEAT TREATMENT: (DIMENSIONS OF CROSS SECTION I.D.=2½" O.D.=5½ - 4¼")

QUENCH TEMP., °F. 1650 TIME OF HOLD, HRS. 6 MEDIUM W.Q.

DRAW TEMP., °F B- 1190 M- 1240 TIME OF HOLD, HRS. 7¼ MEDIUM F.C.

STRESS RELIEF TEMP., °F 570 TIME OF HOLD, HRS. 5½ MEDIUM F.C.

COLD WORK, %: 2% nominal; 2.3 max; 1.8 min; 2.1 ave.

SOAK TEMP. °F 570 5½ F.C.

CHEMICAL COMPOSITION %:

C	Mn	Si	Ni	Cr	Mo	V
.28	.84	.26	--	1.69	.44	.10

AVERAGE TRANSVERSE MECHANICAL PROPERTIES:

		YIELD STRENGTH, PSI .01% SET	YIELD STRENGTH, PSI .1% SET	TENSILE STRENGTH PSI	RED. AREA %	CHARPY * FT. LB.
Before Coldwork:	Breech	102,000	--	128,700	60.1	62.6-64.9 at 70°F
	Muzzle	99,000	--	121,900	64.0	63.7-65.6 at 70°F
After Coldwork:	Breech	114,500	122,000	129,000	60.0	55.5-60.9 at 70°F
	Midlength	112,500	120,000	128,000	58.0	53.7-59.6 at 70°F
	Muzzle	114,000	124,000	127,750	61.0	56.4-65.6 at 70°F
					(Breech)	47.5-50.1 at -40°F

*Range in values is reported.

W.Q. = Water Quench
F.C. = Furnace Cool

Form No. SPOBE-TF-20
L - 3, December 1944

DATA SHEET NO. 1

PERTINENT METALLURGICAL HISTORY OF STEEL

CALIBER AND MODEL: 75mm. M5A1 SERIAL NUMBER: 4K-1391 - F Tube

STEEL PRODUCER: Watertown Arsenal HEAT NUMBER: 4K-1391

STEEL FABRICATOR: Watertown Arsenal METHOD OF FABRICATION: Cent. Casting
Annealed at 1650°F

MACHINING CONTRACTOR: Oldsmobile Div., G.M.C.

FINAL HEAT TREATMENT: (DIMENSIONS OF CROSS SECTION I.D.=2½" O.D.=5½ - 4¼")

QUENCH TEMP., °F 1650 TIME OF HOLD, HRS. 6 MEDIUM W.Q.

DRAW TEMP., °F 1140 TIME OF HOLD, HRS. 6 MEDIUM F.C.

STRESS RELIEF TEMP., °F 570 TIME OF HOLD, HRS. 5½ MEDIUM F.C.

COLD WORK, %: 2% nominal; 2.8 max; 1.7 min; 2.3 ave.
SOAK TEMP. °F 570 5¼ F.C.

CHEMICAL COMPOSITION %:

C	Mn	Si	Ni	Cr	Mo	V
.33	.85	.26	--	1.80	.48	.11

AVERAGE TRANSVERSE MECHANICAL PROPERTIES:

		Yield Strength, PSI .01% Set	Yield Strength, PSI .1% Set	Tensile Strength PSI	Red. Area %	Charpy* Ft. Lb.
Before Coldwork:	Breech	118,750	--	154,000	48.4	32.2-37.0 at 70°F
	Muzzle	125,000	--	156,000	46.1	39.1-39.9 at 70°F
After Coldwork:	Breech	136,250	149,000	160,250	43.9	30.3-31.4 at 70°F
	Midlength	137,500	150,500	160,750	40.6	32.2-32.6 at 70°F
	Muzzle	140,000	154,000	163,500	47.2	34.6-35.0 at 70°F
					(Breech)	14.2-16.4 at -40°F

*Range in values is reported.
W.Q. = Water Quench
F.C. = Furnace Cool

DATA SHEET NO. 1

PERTINENT METALLURGICAL HISTORY OF STEEL

CALIBER AND MODEL: 75mm. M5A1 SERIAL NUMBER: 40-209 - G Tube

STEEL PRODUCER: Watertown Arsenal HEAT NUMBER: 40-209

STEEL FABRICATOR: Watertown Arsenal METHOD OF FABRICATION: Cent. Casting Annealed at 1650°F

MACHINING CONTRACTOR: Oldsmobile Div., G.M.C.

FINAL HEAT TREATMENT: (DIMENSIONS OF CROSS SECTION I.D.=2¼" O.D.=5½ -4-1/4")

QUENCH TEMP., °F	1650	TIME OF HOLD, HRS.	6	MEDIUM	W.Q.
DRAW TEMP., °F	1050	TIME OF HOLD, HRS.	6	MEDIUM	F.C.
STRESS RELIEF TEMP., °F	570	TIME OF HOLD, HRS.	5½	MEDIUM	F.C.

COLD WORK, %: 2% nominal; 1.5 max; .75 min; 1.1 ave.

SOAK TEMP. °F 570 5½ F.C.

CHEMICAL COMPOSITION %:

C	Mn	Si	Ni	Cr	Mo	V
.33	.83	.30	--	1.76	.46	.115

AVERAGE TRANSVERSE MECHANICAL PROPERTIES:

		YIELD STRENGTH, PSI .01% SET	YIELD STRENGTH, PSI .1% SET	TENSILE STRENGTH PSI	RED. AREA %	CHARPY* FT. LB.
Before Coldwork:	Breech	153,750	--	196,000	35.4	17.4-17.8 at 70°F
	Muzzle	152,500	--	190,000	29.4	17.9-17.9 at 70°F
	Muzzle[1]	148,750	--	187,500	26.5	26.2-27.7 at 70°F
After Coldwork:	Breech	168,750	185,000	196,750	33.8	12.4-14.8 at 70°F
	Midlength	167,500	183,750	196,500	30.5	13.4-14.5 at 70°F
	Muzzle	177,500	193,750	199,500	34.4	13.6-13.6 at 70°F
					(Breech)	5.3- 8.3 at -40°F
					(Midlength)	4.6- 8.3 at -40°F
					(Muzzle)	7.2- 8.3 at -40°F

REMARKS:

*Range in values is reported.

1. After maximum discard. Original discard may be insufficient and data are not as representative of metal as are those from muzzle end where maximum discard was taken. With 44" additional discard at muzzle, there was no appreciable change in strength or impact resistance, but reduction in area was 29%.

W.Q. = Water Quench
F.C. = Furnace Cool

DATA SHEET NO. I

PERTINENT METALLURGICAL HISTORY OF STEEL

CALIBER AND MODEL: 76mm. M1A2 SERIAL NUMBER: 4Q-1481-I Tube

STEEL PRODUCER: Watertown Arsenal HEAT NUMBER: 4Q-1481

STEEL FABRICATOR: Watertown Arsenal METHOD OF FABRICATION: Cent. Casting Annealed at 1650°F

MACHINING CONTRACTOR: --

FINAL HEAT TREATMENT: (DIMENSIONS OF CROSS SECTION I.D.= 2.0" O.D.=8-1/4 to 5½")

QUENCH TEMP., °F 1650 TIME OF HOLD, HRS. 6 MEDIUM W.Q.

DRAW TEMP., °F 1260 TIME OF HOLD, HRS. 6 MEDIUM F.C.

STRESS RELIEF TEMP., °F ______ TIME OF HOLD, HRS. ______ MEDIUM ______

COLD WORK, %: 6% nominal; 8.4 max; 3.9 min; 6.0 ave.
SOAK TEMP. °F 570 5½ F.C.

CHEMICAL COMPOSITION %:

C	Mn	Si	Ni	Cr	Mo	V
.28	.67	.20	nil	.94	.55	.06

AVERAGE TRANSVERSE MECHANICAL PROPERTIES:

		YIELD STRENGTH, PSI .01% SET	YIELD STRENGTH, PSI .1% SET	TENSILE STRENGTH PSI	RED. AREA %	CHARPY * FT. LB.
Before Coldwork:	Breech	88,500	---	110,600	40.3	
	Muzzle	88,000	--	109,000	64.4	
After Coldwork:	Breech	103,440	110,625	116,000	55.7	32-37 at 70°F
	Midlength	100,000	108,750	113,250	54.7	54-59 at 70°F
	Muzzle	105,500	112,750	116,400	60.4	58-68 at 70°F
					(Breech)	14-22 at -40°F
					(Midlength)	13-18 at -40°F

*Range in values is reported.

Smooth bore tube.
W.Q. = Water Quench
F.C. = Furnace Cool

DATA SHEET NO. 1

PERTINENT METALLURGICAL HISTORY OF STEEL

CALIBER AND MODEL: 75mm, M5, M6 SERIAL NUMBER: 5J-448 - KTube

STEEL PRODUCER: Watertown Arsenal HEAT NUMBER: 5J-448

STEEL FABRICATOR: Watertown Arsenal METHOD OF FABRICATION: Cent. Casting
Annealed at 1650°F

MACHINING CONTRACTOR: Watertown Arsenal

FINAL HEAT TREATMENT: (DIMENSIONS OF CROSS SECTION I.D.=2¼" O.D.=5½"-4½")

QUENCH TEMP., °F 1600 TIME OF HOLD, HRS. 6½ MEDIUM W.Q.

DRAW TEMP., °F 1170 TIME OF HOLD, HRS. 6½ MEDIUM F.C.

STRESS RELIEF TEMP., °F 570 TIME OF HOLD, HRS. 5½ MEDIUM F.C.

COLD WORK, %: 2 nominal
SOAK TEMP. °F 570 5½ F.C.

CHEMICAL COMPOSITION %:

C	Mn	Si	Ni	Cr	Mo	V	S	P
32	.89	.31	--	1.80	.38	.12	.024	.009

AVERAGE TRANSVERSE MECHANICAL PROPERTIES:

		Yield Strength, PSI .01% Set	Yield Strength, PSI .1% Set	Tensile Strength PSI	Red. Area %	Charpy* Ft. Lb.
Before Coldwork:	Breech	125,000	136,900	156,000	44.0	40.7-30.9 at [illegible]
	Muzzle	125,000	136,800	153,000	36.0	44.1-4.4 at [illegible]
After Coldwork:	Midlength	125,600	143,100	153,300	44.0	[illegible] at [illegible]
	Muzzle	137,000	149,000	154,600	47.2	[illegible] at [illegible]

(Midlength) [illegible]

Muzzle [illegible]

*Range in values is reported.

W.Q. = Water Quench
F C = Furnace Cool

Form No. SPOBE-TF-28
L - 30 December 1944

DATA SHEET NO. I

PERTINENT METALLURGICAL HISTORY OF STEEL

CALIBER AND MODEL: 75mm. M5A1 SERIAL NUMBER: 4K-1491 - N Tube

STEEL PRODUCER: Watertown Arsenal HEAT NUMBER: 4K-1491

STEEL FABRICATOR: Watertown Arsenal METHOD OF FABRICATION: Cent. Casting Annealed at 1650°F

MACHINING CONTRACTOR: Oldsmobile Div., G.M.C.

FINAL HEAT TREATMENT: (DIMENSIONS OF CROSS SECTION I.D.=2½" O.D.=5½ - 4½")

QUENCH TEMP., °F 1650 TIME OF HOLD, HRS. 6 MEDIUM W.Q.

DRAW TEMP., °F 1000 TIME OF HOLD, HRS. 6 MEDIUM F.C.

STRESS RELIEF TEMP., °F ______ TIME OF HOLD, HRS. ______ MEDIUM ______

COLD WORK, %: None

CHEMICAL COMPOSITION %:

C	Mn	Si	Ni	Cr	Mo	V	S	P
.34	.83	.29	--	1.82	.54	.12	.021	.015

AVERAGE TRANSVERSE MECHANICAL PROPERTIES:

	Yield Strength, PSI .01% Set	Yield Strength, PSI .1% Set	Tensile Strength PSI	Red. Area %	Charpy * Ft. Lb.
Breech**	152,500	--	202,500	31.0	10.9-13.3 at 70°F
Muzzle**	153,750	--	200,750	37.1	14.5-15.5 at 70°F
Breech	156,250	176,000	203,500	35.5	11.8-13.8 at 70°F
Midlength	159,250	178,000	204,250	34.5	12.1-13.8 at 70°F
Muzzle	162,500	177,000	201,000	32.0	12.4-13.6 at 70°F
				(Breech)	10.6-10.6 at -40°F
				(Midlength)	7.2-10.0 at -40°F
				(Muzzle)	8.3- 9.4 at -40°F

*Range in values is reported.

W.Q. = Water Quench
F.C. = Furnace Cool
** Inspection Report

APPENDIX C

The Crack System

APPENDIX C

The Crack System

Data pertaining to the number of cycles for failure and to factors affecting this number have been discussed in the main body of the report. These data were used for establishing a design procedure based on end of life. In this appendix is given an evaluation of the condition of various cylinders at the end of the hydraulic fatigue test. The crack system is described in detail, especially that existing in the low strength (A,B,C,D) tubes. Also, similarities between results of service firing tests and laboratory tests are indicated.

The procedure used in studying the crack system of these cylinders including one or more, but not necessarily all of the following steps: (1) examination of the fissure, (2) study of the surface of the fracture, and (3) measurement of the cracks on a disc cut from the cylinder or pieces of the cylinder normal to the axis and at the region of maximum progressive stress-damage. The disc was surface ground and macroetched in order to reveal clearly the cracks. The disc that was cut may at times be made up of as many as three pieces because the cylinder was frequently cut longitudinally on a plane normal to the radial plane of the fissure and the half with the fissure was then split open in order to see the fracture.

The cracks in the macroetched disc are known as the "remaining cracks". This is because the failure occurs at a crack which penetrates the full thickness of the cylinder. This crack usually was not visible as such in many of

the macroetched pieces of discs because one side of the crack formed one of the edges of the pieces making up the disc. Knowledge about the distribution of the remaining cracks and the depths to which the cracks grow helps in establishing the correlation between service and laboratory tests.

The fissure in the failed cylinders revealed features about the relative ductile behavior of the metal under the test conditions. In some cases considerable distortion of the metal with extensive bulging of the cylinder occurred. In other cases there was less distortion with little bulging. Sometimes the fracture extended almost the full length of the cylinder and at other times only a minute fissure appeared on the outside.

The surface of the fracture revealed the occurrence of several zones. Limiting inspection to the fracture which caused final failure, there could be seen adjacent to the bore in Zone one a region of fine texture. This texture roughened as the first zone blended with the second zone indicating that less rubbing of the sidewalls had occurred during the hydraulic fatigue test. At the base of the second zone it is considered that the cylinder had yielded appreciably and the direction of the crack started to change and became radial. The base of the next or third zone is the point where the change in direction of crack was completed and the direction of the crack became radial. The crack continued to propagate radially throughout this next or fourth zone with the metal tearing apart and leaving a coarse texture on the fracture until failure in shear occurred. The region of shear is the fifth zone. The crack penetrated the full thickness of the cylinder which had bulged and therefore

thinned, especially at the region of maximum damage. The thickness of the wall at the point of maximum progressive stress-damage was measured. The five measurements that were made are as follows:-

Zone 1 - Depth from bore to base of first zone - or zone of fine texture

Zone 2 - Depth from bore to base of second zone where direction of crack started to change

Zone 3 - Depth from bore to base of third zone where crack became radial

Zone 4 - Depth from bore to base of fourth zone or to point of shear

Zone 5 - Depth from bore to base of fifth zone or thickness of wall after test.

RESULTS AND DISCUSSION

(A, B, C, D and Cylinders 76mm. Caliber)

Cylinder C9 after failure is shown in Fig. 17. This cylinder had a wall ratio of 1.4 and a wall thickness of .616". The fissure was located at about 4 o'clock. Distortion of the cylinder was apparent and the increase in outside diameter was 0.152". Plastic deformation associated with the rifling was evident around the whole outside circumference as indicated by the arrows in the picture. The cylinder behaved in a uniform manner and the appearance of others was similar.

The bore surface is shown in Fig. 18. It revealed that the distortion caused widening of cracks, all of which followed the groove fillets. The three pieces of the macroetched disc revealed that cracks existed at each of the groove fillets. Examination of the bore surface of this macroetched disc was necessary to detect some of the cracks. In Fig. 19, which is an enlarged photograph of the macroetched disc, definitely measurable cracks can be seen at most of the fillets. All of the deep cracks were wide, conforming with the distortion seen around the outside of the cylinder. The fissure occurred when the crack separating the two pieces shown at the bottom of Fig. 19 penetrated to the outside surface. Final failure was in shear with extensive distortion of the metal. The distance

from the bore surface to the point of shear was 0.42 inch. The thickness of the cylinder at the point of fissure was 0.5 inch so that the wall thickness was thinned by about 0.1 inch. The maximum depth of the "remaining cracks" was 0.135 inch. Further reference will be made later to the depth to point of shear and to the maximum depth of the "remaining cracks".

The tendency of the cracks to slope under the grooves is also shown in Fig. 19. This was a characteristic in all coldworked tubes made of low strength steel. However, the thinner the tube, the less was this tendency. The ranges in angle between the radius and the axis of the crack were: 0 to 14°, 9 to 22°; 10 to 25°; and 13 to 34° for cylinders of 1.2, 1.4, 1.6 and 1.8 wall ratios, respectively from the A, B, C and D tubes. In thick-wall cylinders it was especially apparent that the average angle also tended to increase as the internal pressure increased. The trend was not uniform in thin wall tubes. The average angles were as follows:

Wall Ratio	Internal Pressure psi	Average Angle Between Crack and Radius degrees
1.8	62,500	25
1.8	59,000	23
1.8	48,500	18
1.6	46,000	22
1.6	44,000	19
1.6	38,250	17
1.6	36,250	16
1.4	28,750	13
1.4	27,500	17
1.2	18,000	10
1.2	16,500	10

Part of the fractured surface of Cylinder C9 after the crack which caused failure was opened up is shown in Fig. 20. The bright and dark irregular areas over most of the fracture in the lower part of the figure were formed when the specimen was bent to open up the crack. The bright areas were crystalline and reflect incomplete hardening of the steel on the quench. These irregular areas

have no bearing on progressive stress-damage. The places where the fissuring occurred during the hydraulic fatigue test are at the top of the figure and along the bore edge; at these locations, indicated by arrows, can be seen the progressive stress-damage zones starting at the four groove fillets which are visible. Maximum depths of such zones are seen toward the top of the picture.

The extreme conditions in appearance of fissures are shown in Figs. 21 and 22. In general, the latter is considered a more ductile type of break than the former. A sketch of the appearance of the fissures in cylinders is shown in Fig. 23. The more ductile appearance was obtained when the wall ratio tended to be large, the internal pressure low, and when the steel had high impact resistance. In attempting to measure the ductility, nonuniform results were obtained. It was apparent that the measurement of the change in diameter was a more sensitive method than measuring the thickness of the wall at the point of fissure in evaluating ductility.

Although the room temperature impact resistance of the steels in the A, B, C and D tubes ranged from 16 to 75 ft-lbs no measurable effect of toughness in this range was apparent on the life of the cylinder. It has been previously reported[12] that for heat-treated-to-strength forgings in the range of 11 to 24 ft-lbs impact resistance at yield strength levels of 150,000 to 163,000 psi, better life was definitely obtained at high impact levels than at low impact levels. At low yield strength levels the importance of toughness as measured by impact resistance was not evident upon life, but was definitely evident upon the tendency to fail brittlely. Prior experience also revealed that with brittle steel in heat-treated-to-strength cylinders the larger the wall ratio, the greater was the tendency to brittle failure; also the smaller the wall ratio, the greater was the frequency for occurrence of ductile failures. It may be that at the yield strength levels

12. Memo. Report 731/138-1: "Examination of Test Cylinders 29462B, 29466B, 29460B, 29464B, 29469B and 69272 Subjected to Repeated Internal Hydraulic Pressure" By: J. B. Cohen, 12 December 1944
Memo. Report 731/124-1: "Progress Report to the Subcommittee on Gun Forgings" By: P. R. Kosting and Capt. D. H. Newhall

of the steels of the A, B, C and D tubes the favorable residual stress system in coldworked tubes is counteracting the detrimental effect revealed by poor toughness.

The poor macrostructure evident in Fig. 19 had no measurable effect on progressive stress damage. It did have another effect, however; namely, favoring the formation of tears on the outside of the cylinders toward the end of test when bulging occurred. These tears were not generally affected by the cracks starting at the bore surface, as shown in Fig. 24.

One of the minor effects of segregations causing this poor macrostructure was the occasional local influence on the direction of the growth of the crack. Inclusions likewise have a similar minor effect. When such defects occurred at the bore surface within the groove, the early formation of a crack was favored. However, such cracks are considered to have spread quickly to the groove fillet and to have become part of the predominant crack system at the fillet without any measurable effect on life.

Depth of Cracks

The test of Cylinder C12 was stopped after some 20,322 cycles without any evidence of failure being imminent. On the macroetched disc from midsection, cracks were observed; the greatest depth was 0.025 inch.

The test of Cylinder C11 was stopped when failure was imminent but when full pressure was still being withstood. The outside of the cylinder is shown in Fig. 25. The distortion where fissuring would soon occur is evident. This spot is indicated by the arrow in the picture. The macroetched section at this spot is shown in Fig. 26. The deep crack at the top of the figure had propagated almost 80% of the wall thickness. The depth of the crack was .22 inch. The distortion on the outside edge of the cylinder opposite the root of this crack is discernible.

The depths of the various zones on most of the fractures in the cylinders from the A, B, C and D tubes are listed in Table II. The zones which were most easily identified were Zones 4 and 5. Zone 1 was the next easiest but its junction with Zone 2 was nonuniform. The limits of the zones were, in general, very difficult to identify and to measure. Poor reducibility was experienced.

The depth to the point of shear as influenced by internal pressure is shown in Fig. 27. The depth of crack (or depth to point of shear) at which the cylinder would fail decreases as the internal pressure increased. The relationship[12] between internal pressure, depth of crack for failure and wall ratio which has been worked out for brittle material[13] was not found to be adequate with these cylinders which behaved essentially in a ductile manner and also had a residual stress system. The cylinders without any cracks would rupture when subjected to the maximum internal pressure calculated by means of the bursting pressure factor. The bursting pressure factor developed for ductile metal by Blair[14] was simple to use and was found to be accurate when gun sections with wall ratios up to 2 were tested. At the other extreme when the crack existed completely through the wall thickness, no pressure would be required to rupture the cylinder. The pressure required to rupture the cylinder when a crack extended part way through the wall thickness was calculated by assuming that the relationship between internal pressure and depth to point of shear would be represented by the equation for an ellipse. An

---

12. "Stresses in Thick Wall Cylinders" - Sixth International Congress for Applied Mechanics, 1946; R. Beeuwkes, WAL Report No. 730/419.
13. "Theory of Elasticity", McGraw Hill Book Co., 1934, p. 144, By: S. Timoshenko
14. "Letter", By: J. S. Blair: ENGINEERING, V. 159, January-June 1945, p. 356 and "The Strength of Thick Hollow Cylinders Under Internal Pressure", By: Gilbert Cook and Andrew Robertson, ENGINEERING, V. 1911, p. 786

equation was developed involving the tensile strength (ts) of the steel before coldwork, the internal pressure (IP), the inside diameter (id) and wall ratio (W) of the cylinders and the depth to point of shear (a), as follows:

$$a = \frac{1}{2}\,\frac{W-1}{W^2-1}\,\frac{id}{ts}\sqrt{(ts)^2\,(W^2-1)^2-(IP)^2\,(1.5+W+0.5W^3+W^4)} \quad \ldots\ldots (1)$$

If the bursting pressure factor (bpf) as developed by Blair[14] is used, namely,

$$bpf = \frac{W^2-1}{\sqrt{1.5+W+0.5W^3+W^4}} \qquad \text{then}$$

$$a = \frac{1}{2}\,id\,(W-1)\sqrt{1-\frac{(IP)^2}{(ts)^2\,(bpf)^2}} \qquad \text{or}$$

$$\frac{IP}{ts} = \frac{bpf}{W-1}\sqrt{(W-1)^2-4\left(\frac{a^2}{id^2}\right)} \quad \ldots\ldots\ldots (2)$$

Equation (2) is in a form which is more generally applicable than is Equation (1) because internal pressure is expressed as a fraction of tensile strength and depth of crack as a fraction of internal diameter. The curves of Equation (1) for various wall ratiosare shown in Fig. 27 and that of Equation (2) is shown in Fig. 28. In Fig. 27 data for the A, B, C and D cylinders are shown, and in Fig 28 those for the K cylinders, to be mentioned later, are shown. The observed data at the smaller wall ratios are consistent with the curves, but as the wall ratio increases above 1.8, the curves tend to be conservative. This may indicate the limitations of the empirical approach, although the scatter, in general, is large and the data are few in this region. The data as a whole are considered to respond quite well to this treatment which is helpful in the analysis of the crack system.

The depths of the various zones in the fracture at which final failure occurred tended to decrease with increase in internal pressure as seen from a survey of the data in Table II. ~~Zone 1 is considered to be the depth to which~~ the crack grew before bulging of the cylinder started and the sidewalls no longer

rubbed together. The base of the other zones mark locations where changes occurred in the direction of the stress gradient as the crack propagated.

The maximum depth of the remaining cracks decreased with increase in internal pressure. The remaining cracks were always appreciably smaller than the depth to point of shear. This indicates that if ever any field tests are undertaken to locate and determine the depth of cracks in cannon in order to evaluate the safety of the weapon, complete coverage of the bore must be made in order to find the single potentially dangerous deep crack even though several cracks may be found in the neighborhood.

E, F, G and K Cylinders

The crack systems were partially examined only in Cylinders E5, F5 and G5, these being taken as representative of the centrifugally cast coldworked high-strength tubes. Failure in each case was of the ductile type. In Cylinders E5 and F5 the cracks sloped under the grooves, although the tendency was less pronounced in the case of F5 (121,850 psi yield strength) than in E5 (100,500 psi, yield strength), but in Cylinder G5 (151,700 psi, yield strength) the cracks were essentially radial.

The relationship between depth to point of shear and pressure for the cylinders from the K tube is indicated in Fig. 28. The behavior is consistent with the discussion already presented pertaining to Fig. 27.

N Cylinders

The cylinders from the heat-treated-to-strength centrifugally cast tube "N" failed in a brittle manner when the wall ratio was 1.57 or larger but in a ductile manner when the wall ratio was 1.2. This is consistent with the behavior of heat-treated-to-strength forgings. However, even in the brittle type of break

there was a very limited region of shear. The toughness of steel "N" was similar to that of steel "G" and was not even as good as that of many forgings which have been used in this application.

Safe Depth of Cracks

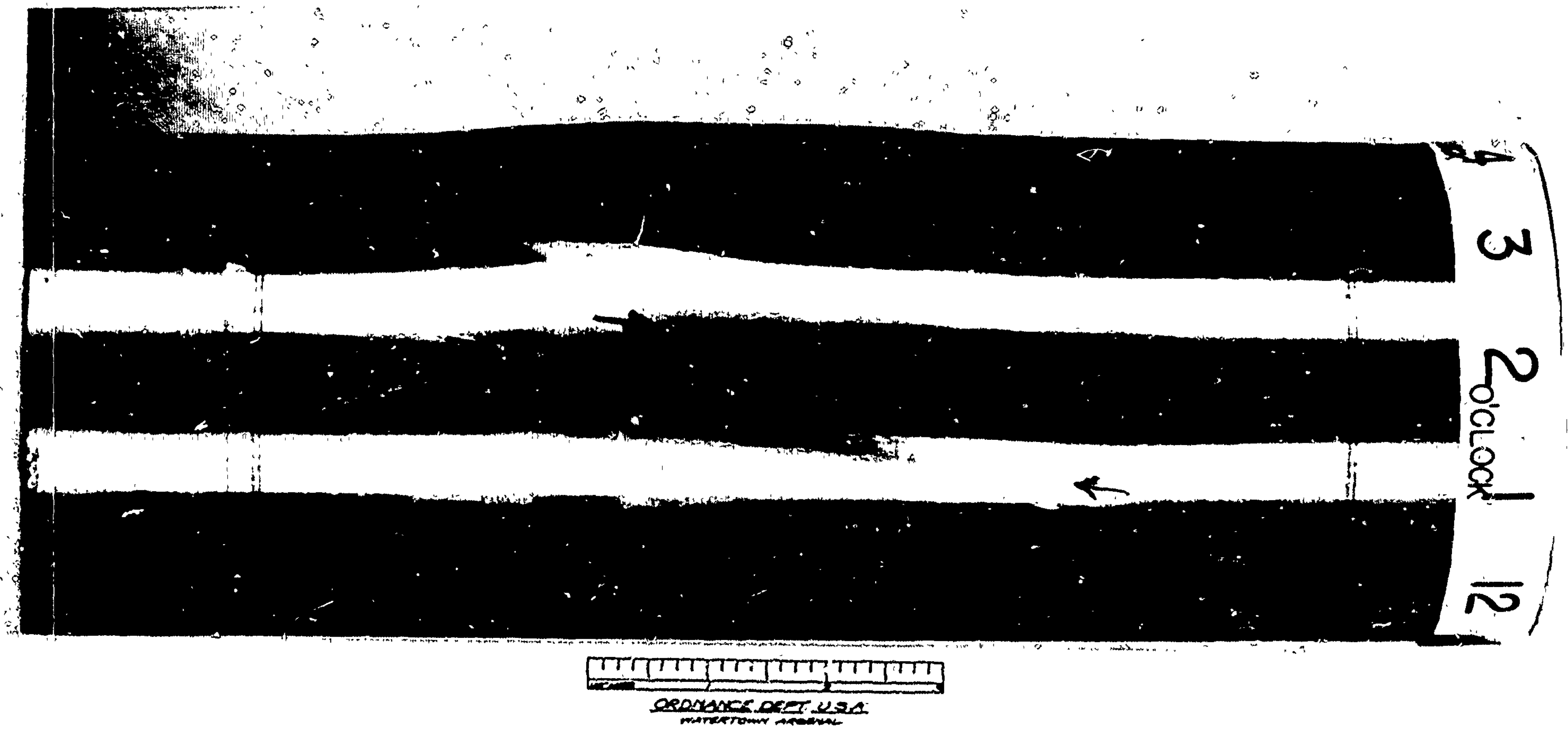
The examination of the crack system in cylinders which were taken out of test before failure and even when fissuring was imminent indicated that cracks are present in the specimen early in the life of the cylinder and that final failure on the last cycle is by shear from the root of the existing deep crack and not by marked radial growth of a shallow crack prior to shear. The trend is for the depth of the crack to the point of shear to increase with decrease in test pressure. As the test pressure decreases the number of relatively deep cracks detected on the macroetched cross-section of the cylinder tends to decrease and the depth of the remaining cracks tends to increase. However, the trend is not uniform and the behavior of cylinders such as C11 indicates that as the pressure decreases further and approaches the endurance limit pressure of the cylinder, the conditions favorable for the preferential growth of one crack improves, and the deeper this one crack grows relative to the others before final failure. At and below the endurance limit pressure no crack will form and grow under test conditions such as these. The examination of cannon after service reveals that many cracks grow indicating again that the test conditions used in this investigation have parallel effects in service when the test pressure is relatively high and that in service the rated maximum powder pressure in conventionally designed guns is much higher than the endurance limit pressure.

The data on Fig. 3 indicate that the strain on the outside of the cylinder increases appreciably toward the end of life. This has also been observed in firing tests. The time in the life of the cylinder at which this strain increases

rapidly appears to be about 60 to 70 percent of the life of the cylinder, probably at the time when the rate of growth of crack begins to be dangerously rapid, but slight permanent change has been observed much earlier that 60 percent of life. Examination of the fracture is taken to indicate that the depth at which the growth is rapid is at the depth of Zone 2. The depth of Zone 2 is therefore temporarily considered to be the safe depth to which cracks may be permitted to grow in service before the gun tube be taken out of service because of progressive stress damage. The problem of detecting this depth in the field is not yet solved.

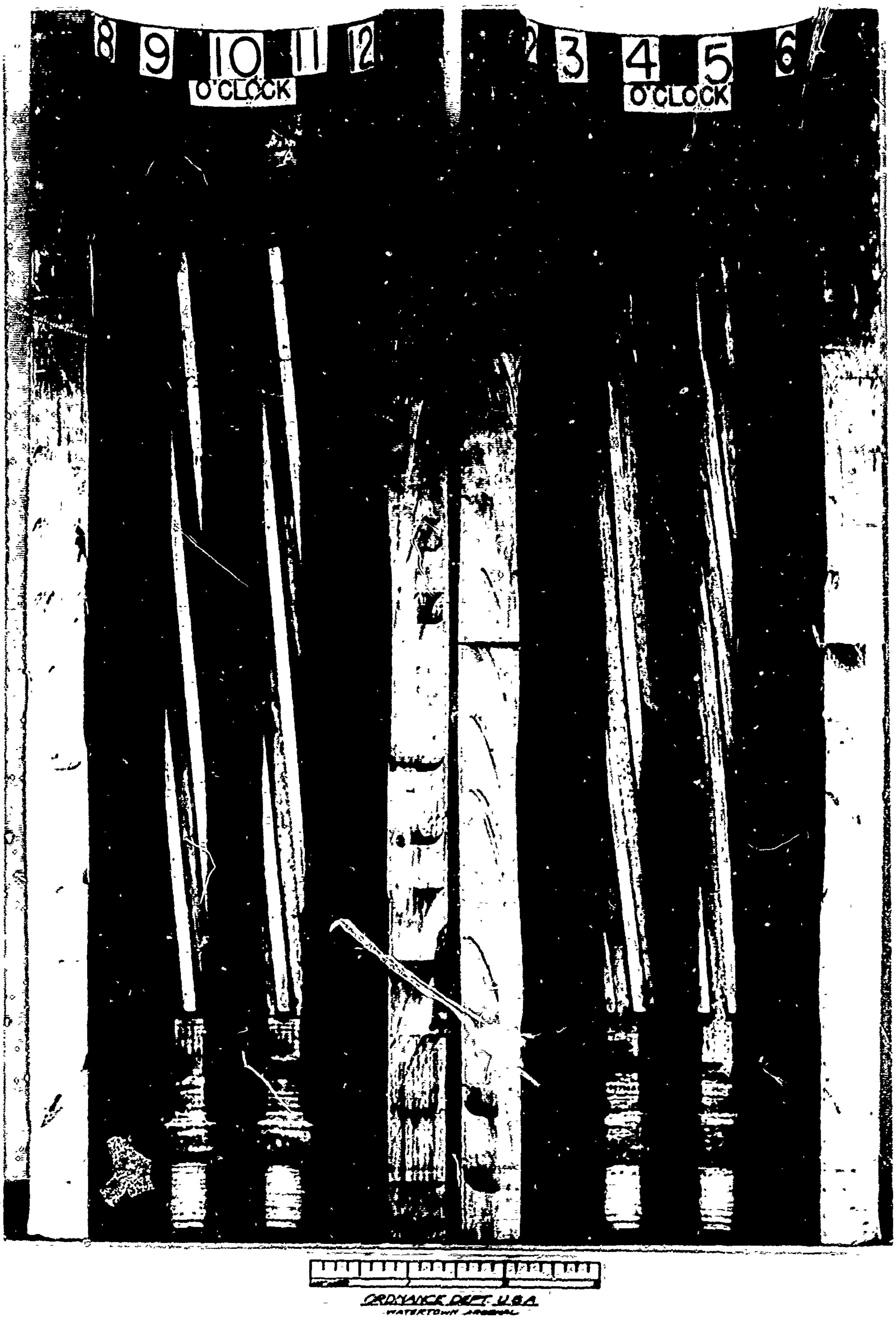
The tendency for cracks to slope under the grooves in coldworked-to-strength gun tubes has been observed in cannon taken from service. This is especially so in the region of the muzzle. The tendency at the origin of rifling is for the cracks to propagate under the lands. This indicates that the stress conditions in this region are different from those in the test as would be expected because of engraving stresses.

The tendency for cracks to grow under the grooves in coldworked-to-strength tubes differs from their behavior in heat-treated-to-strength tubes. In this case the cracks remain radial. Similar behavior has been observed in cannon taken from service although in some weapons when the stress system is different the cracks propagate under the lands. The behavior can not be predicted based on consideration of gun tube design alone, but must include consideration of the mutual effect of design of rotating band and of rifling.



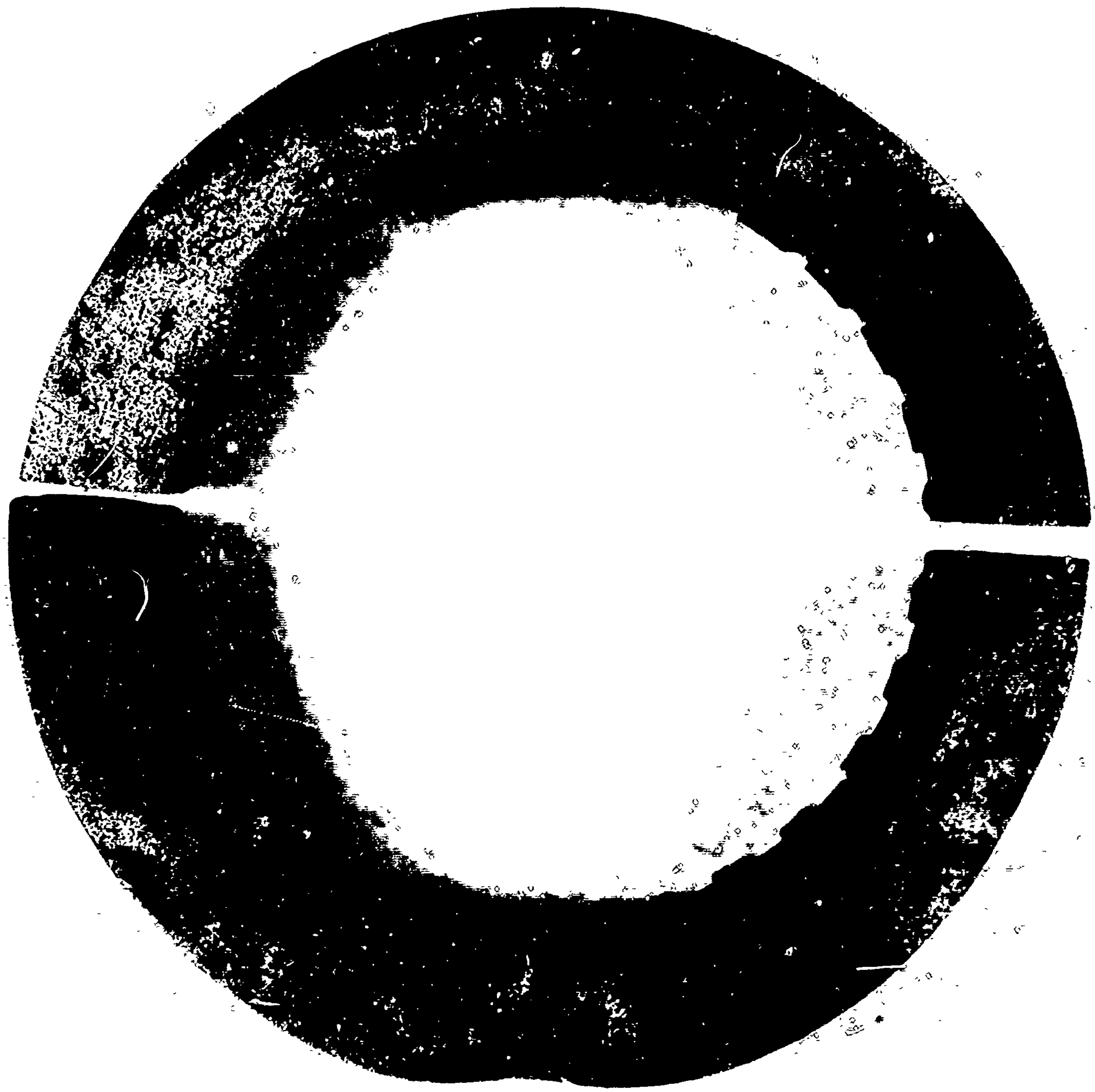
TEST CYLINDER C-9 FROM 76MM TUBE M1A2 49 - 150 AFTER 5002 CYCLES OF HYDRAULIC PRESSURE AT 32,000 PSI, SHOWING LOCALIZED PLASTIC YIELDING OF METAL AT VARIOUS O'CLOCK POSITIONS
8 FEB 1945
WTN.362-794

FIG. 17



BORE SURFACE OF TEST CYLINDER C9 FROM 76MM TUBE M1A2 AFTER 5002 CYCLES OF HYDRAULIC PRESSURE AT 32,000 PSI SHOWING PROGRESSIVE STRESS-DAMAGE CRACKS AT GROOVE FILLETS AT VARIOUS O'CLOCK POSITIONS. 23 FEB 1945 WTN.362-821

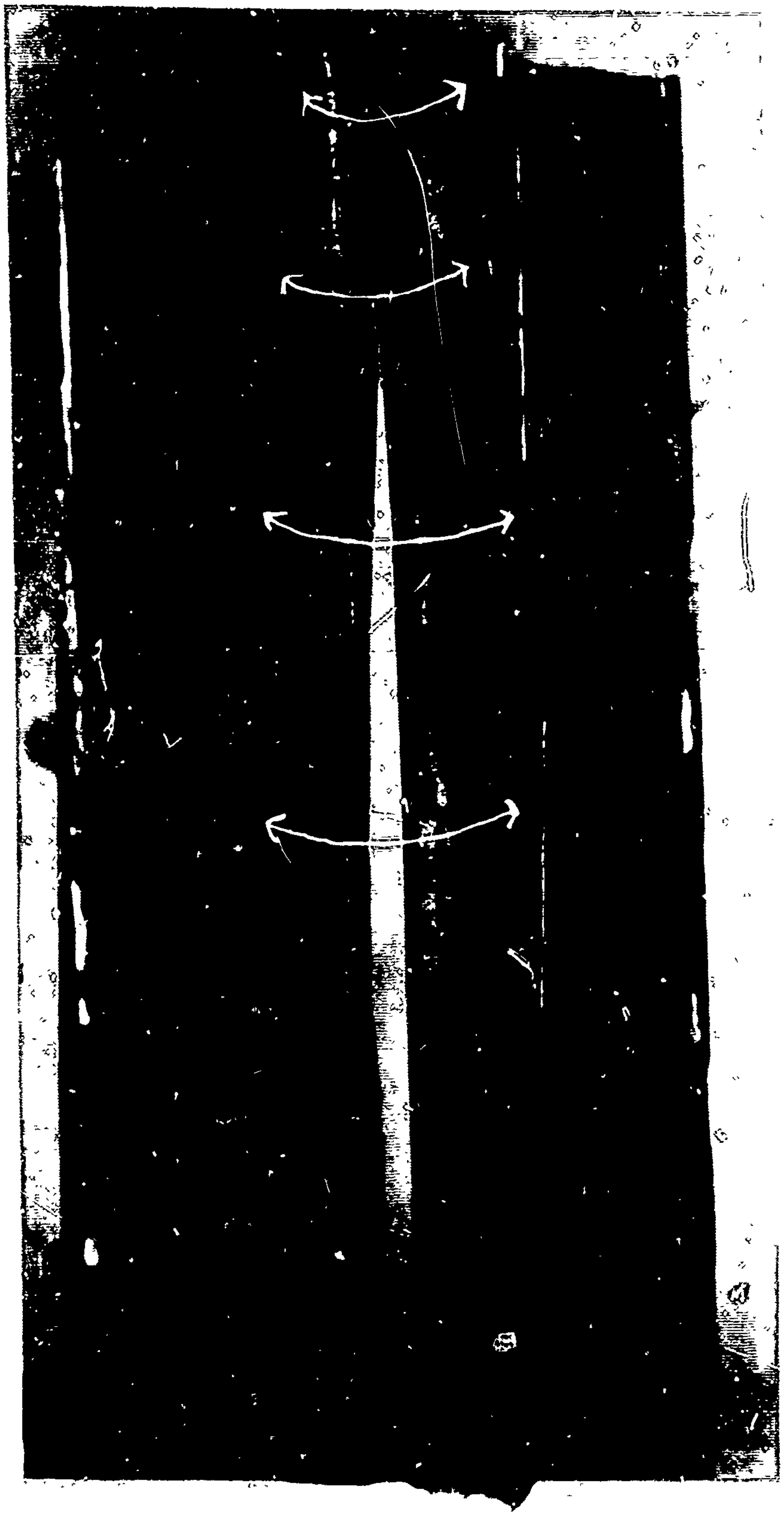
FIG. 18



WATERTOWN ARSENAL

MACROETCHED SECTION 5" FROM END OF TEST CYLINDER C9 AFTER 5002 CYCLES AT 32,000 PSI PRESSURE. MAG. X1½ 5 MAR 1945 WTN 223-5125

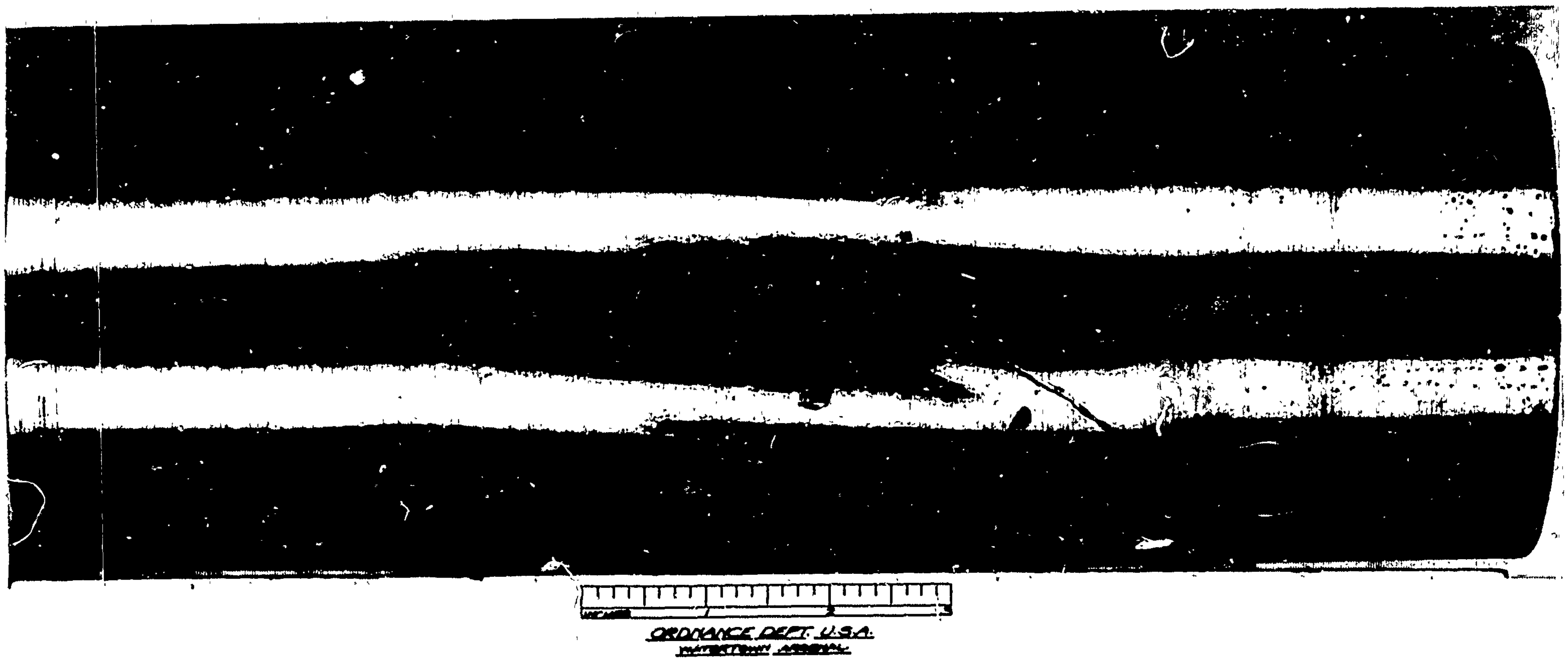
FIG. 19



WATERTOWN ARSENAL

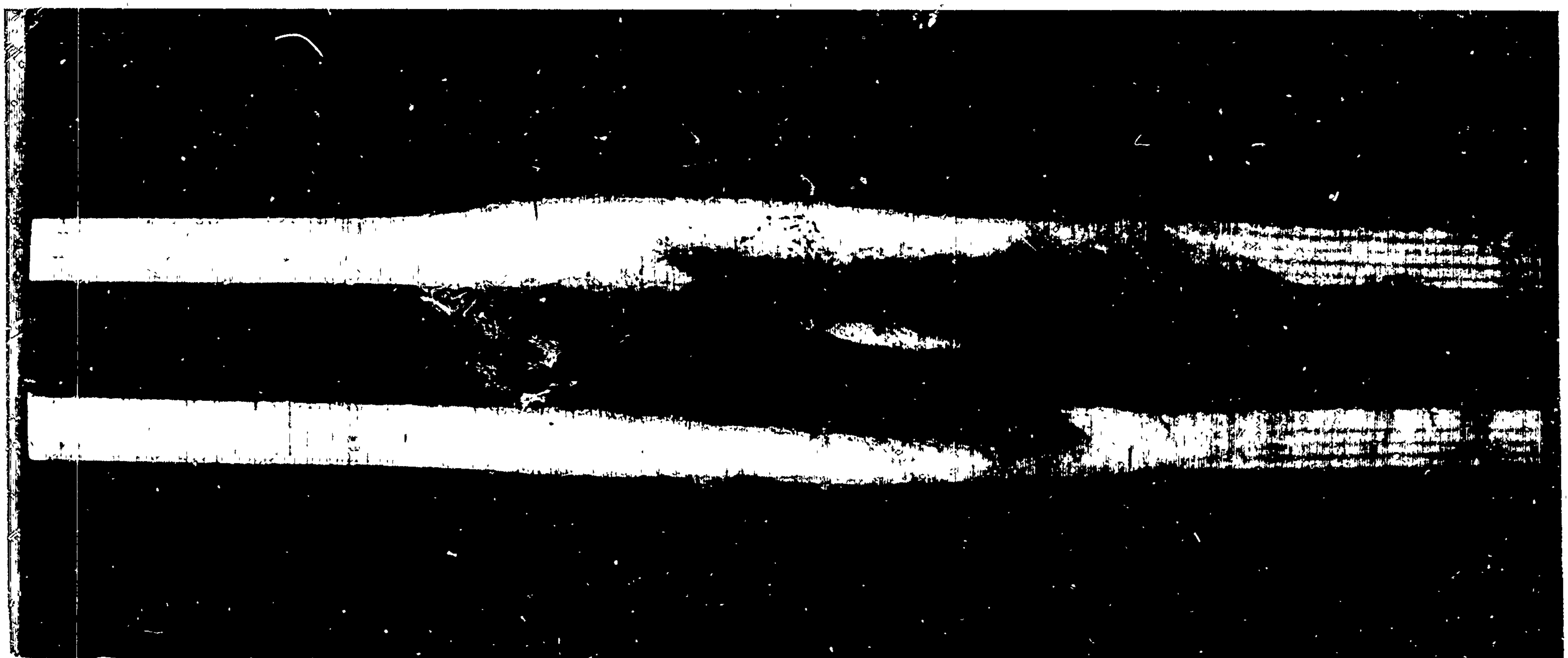
FRACTURE IN TEST CYLINDER C9 WHICH FAILED AFTER 5002 CYCLES AT 32,000 PSI PRESSURE
20 MAR 1945 WTN.362-835

FIG. 20



TEST CYLINDER A-11 FROM 76MM TUBE M1A2 3J-2524 AFTER 1015 CYCLES OF HYDRAULIC PRESSURE AT 30,000 PSI. 20 NOV 1944 WTN.362-694

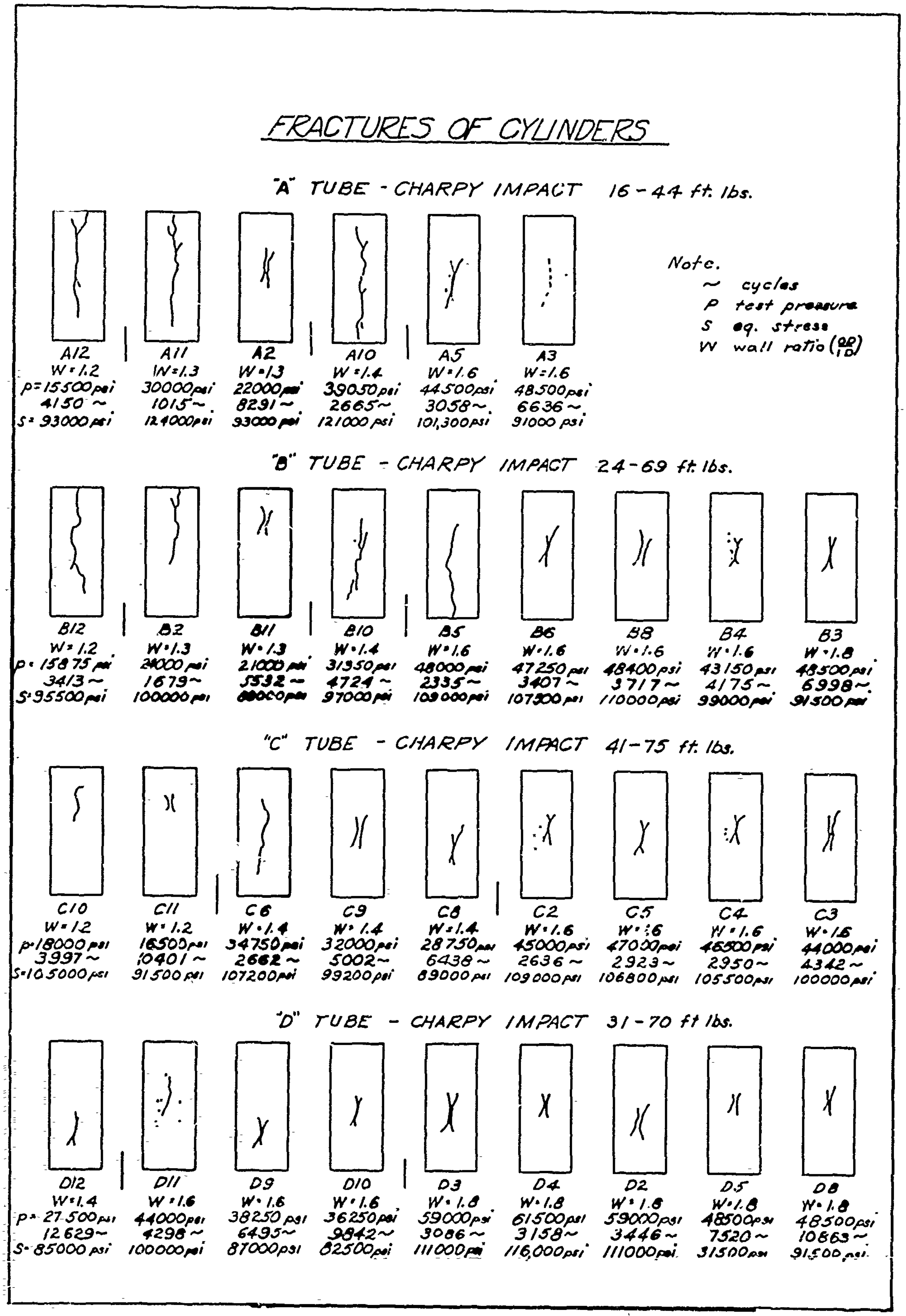
FIG. 21



[redacted]

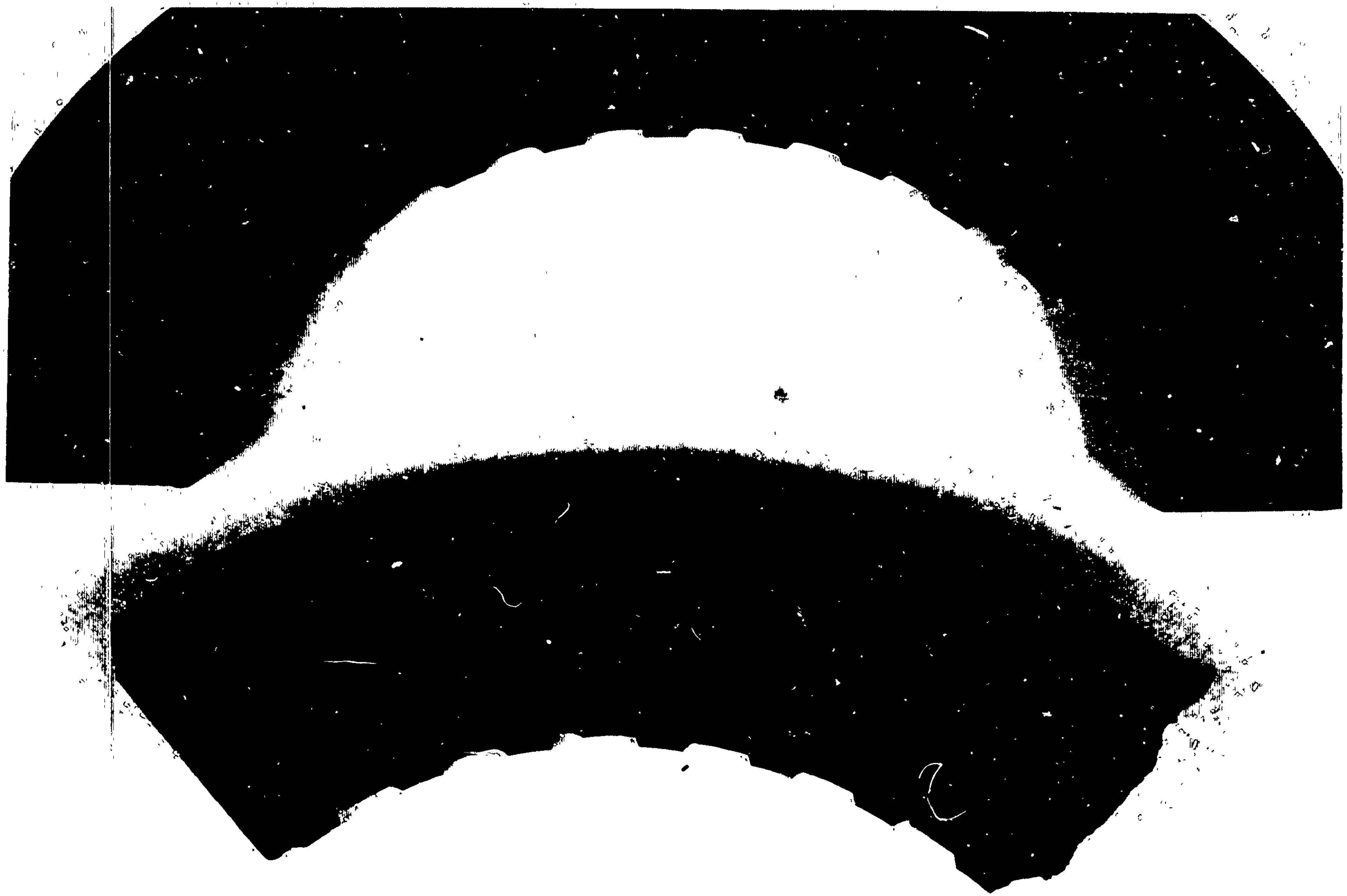
TEST CYLINDER C5 FROM 76MM TUBE M1A2 4G-150 AFTER 2923 CYCLES OF HYDRAULIC PRESSURE AT 47,000 PSI. 8 FEB 1945 WTN.362-789

FIG. 22



WTN.639-944

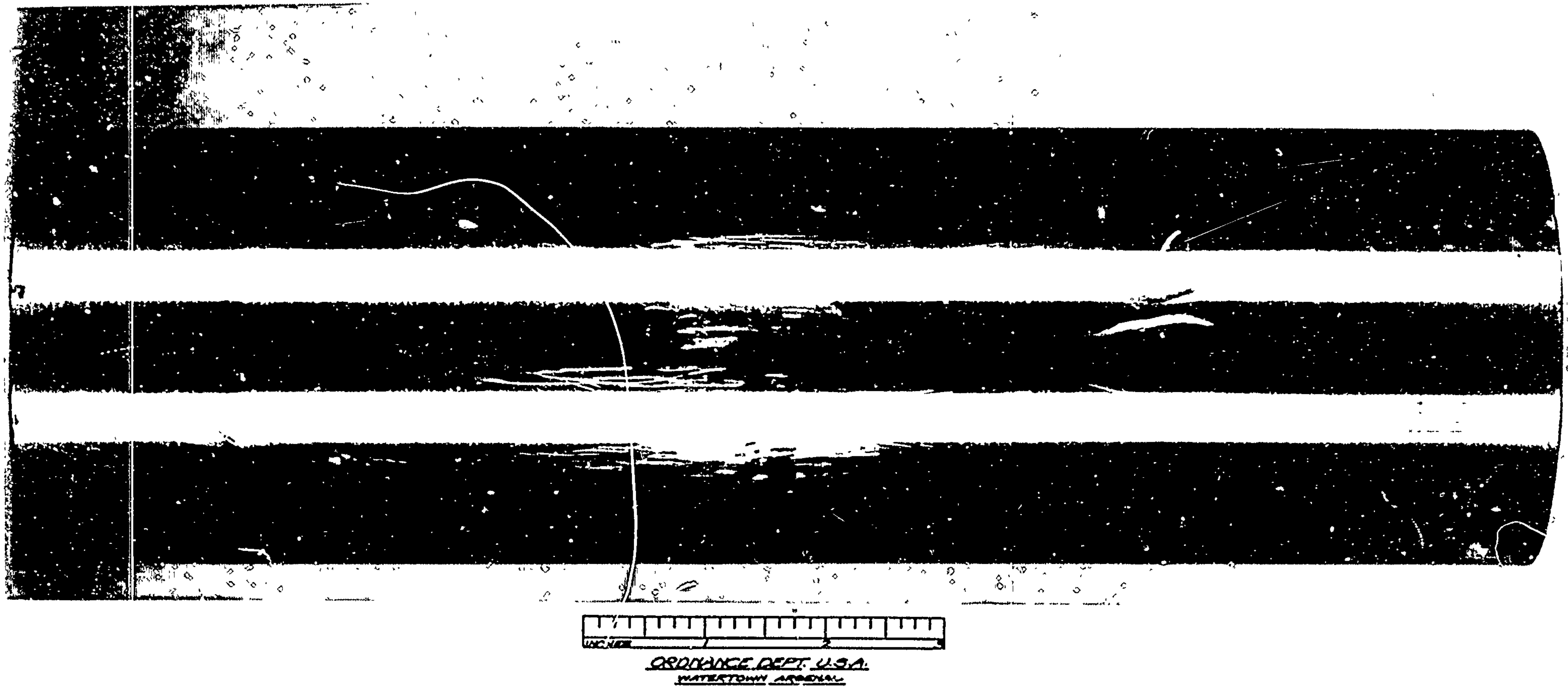
FIG. 23



WATERTOWN ARSENAL

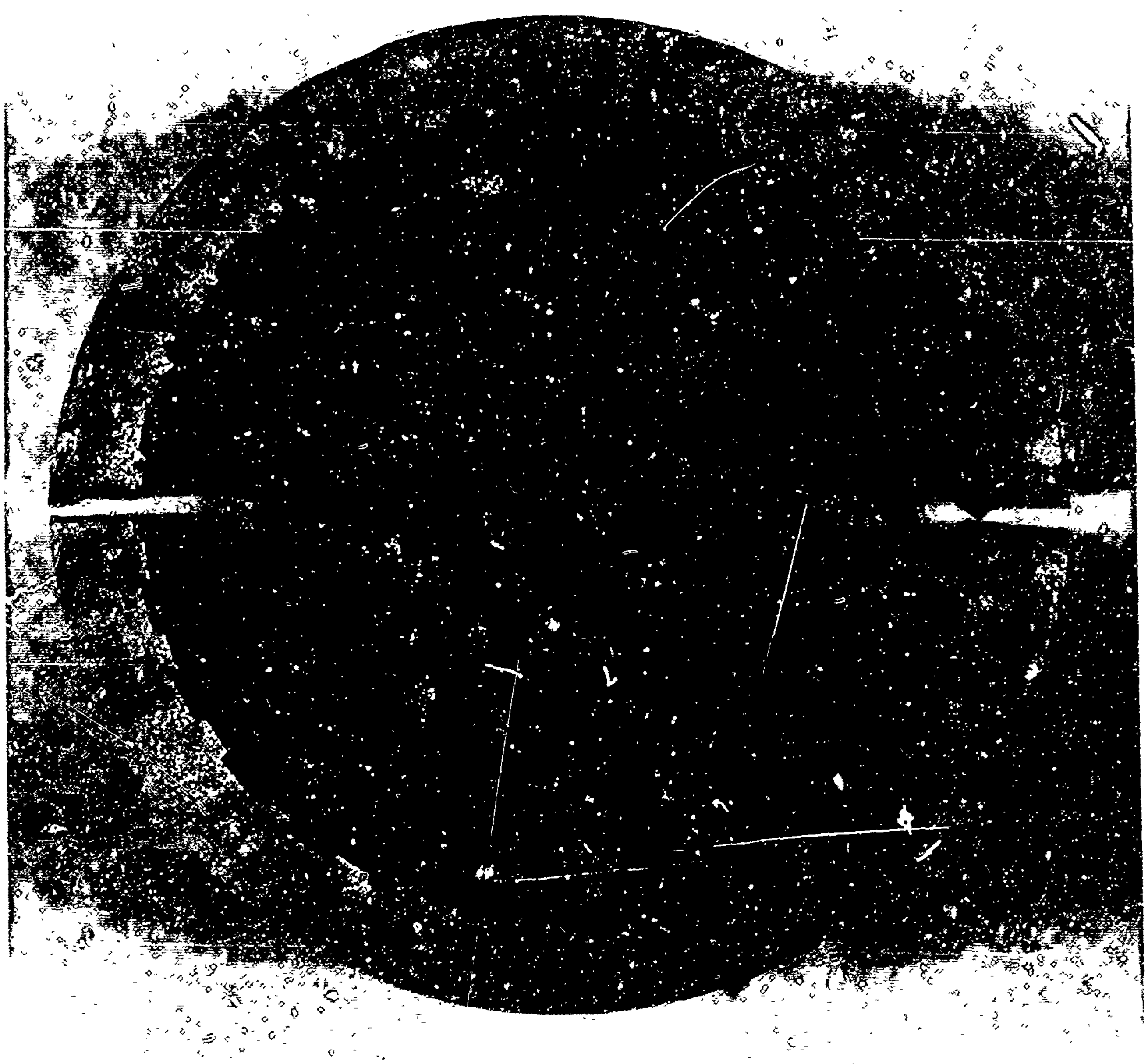
GROOVE FILLETS IN MACROETCHED DISC FROM TEST CYLINDER A8 AFTER 798 CYCLES AT 54,000 PSI PRESSURE. MAG. X2   8 FEB 1945   WTN.362-796

FIG. 24



FATIGUE TEST CYLINDER FROM 76MM M1A2 4G-150-C11 AFTER 10401 CYCLES OF HYDRAULIC PRESSURE AT 16,500 PSI.
2 FEB 1945
WTN.362-783

FIG. 25



WATERTOWN ARSENAL

MACROETCHED SECTION 3.1" FROM END OF TEST CYLINDER C11 AFTER 10,401 CYCLES AT 16,500 PSI PRESSURE. MAG. 1½ 27 FEB 1945 WTN.362-829

FIG. 26

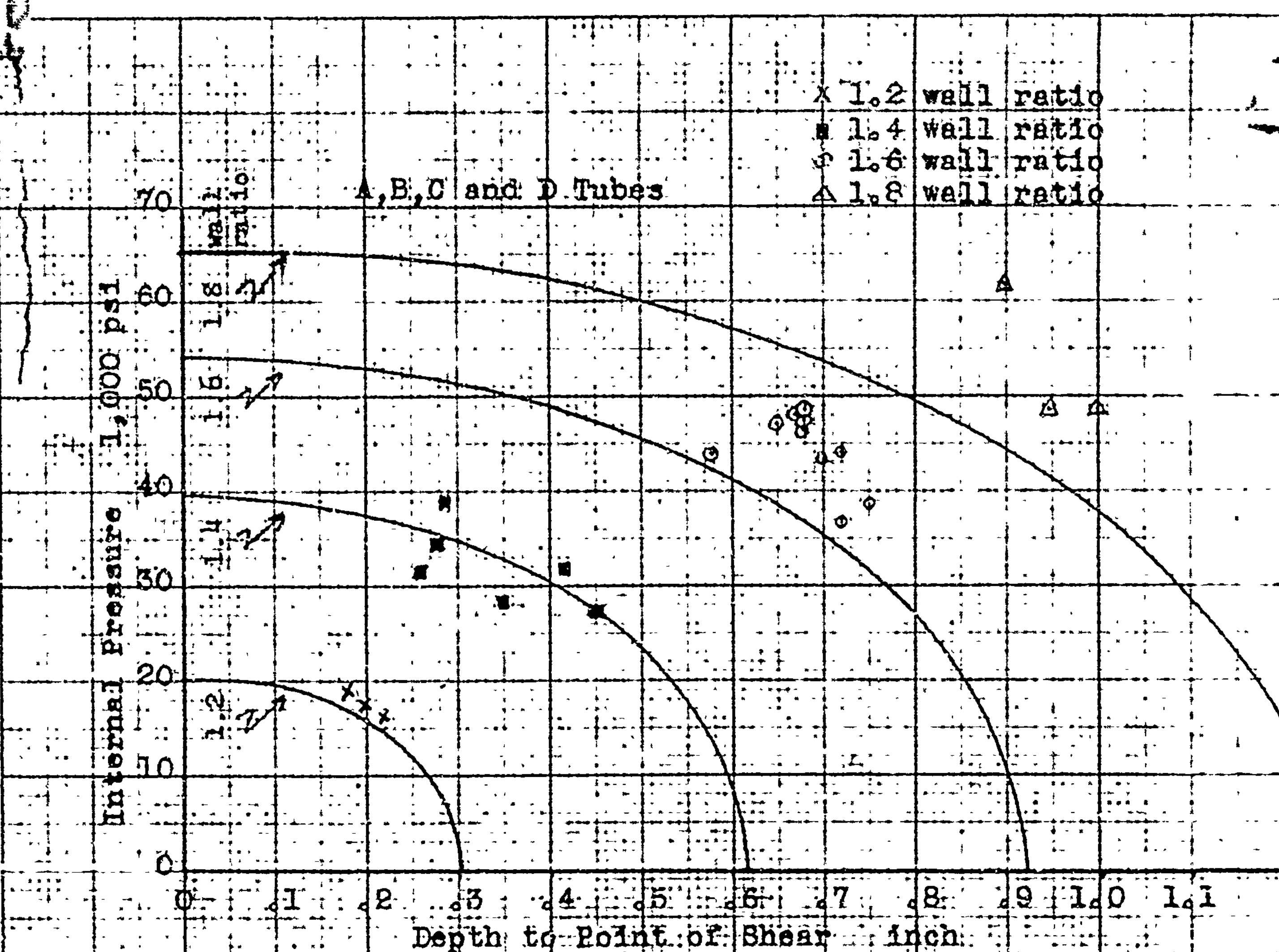
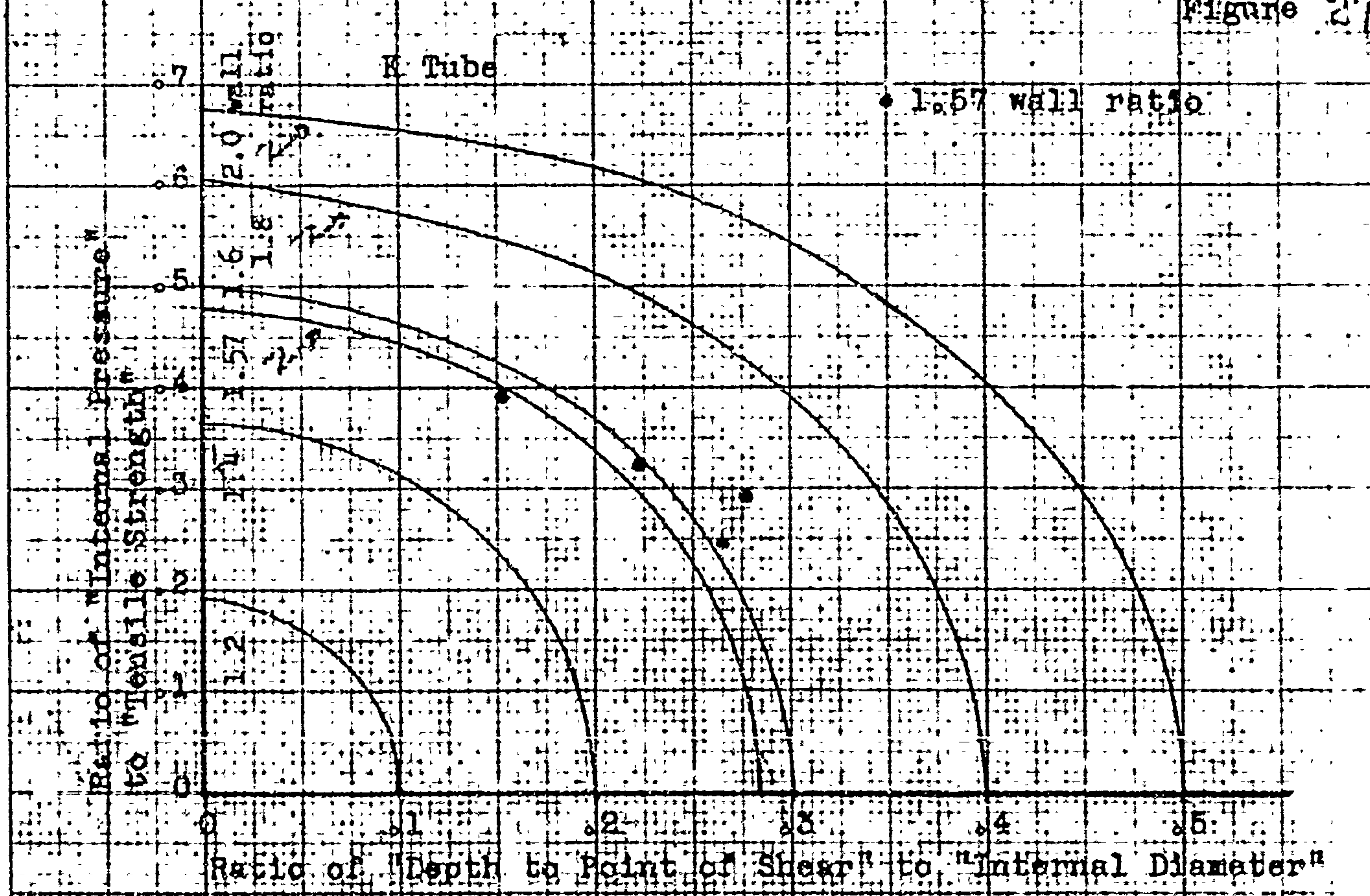


Figure 27



RELATIONSHIP BETWEEN INTERNAL PRESSURE AND DEPTH OF CRACK TO POINT OF SHEAR

Figure 28